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Adsorptive Mechanism on Activated Carbon in the Liquid Phase. III. The Relationship between the Physical Constants of Organic Compounds and Their Adsorbabilities on Activated Carbon from an Aqueous Solution[1)]

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In order to evaluate the adsorbability for a given activated carbon from a knowledge of the physical properties of the adsorbate, the partition coefficients (α) of 93 organic compounds between the solution and the adsorbed phases at an infinite dilution have been calculated and correlated with the various physical constants. For aliphatic monofunctional compounds, a good linear relationship is obtained between log α and the following physical constants: molecular weight, molar attraction constant, and modified organicity/inorganicity value. This indicates that these physical constants are useful for predicting the adsorbability of aliphatic monofunctional compounds and that a straight line represents the adsorption characteristics of a given activated carbon. The correlation coefficient between the log α value and the physical constants for multifunctional compounds is lower than that for monofunctional compounds. The adsorptive mechanism on activated carbon in an aqueous solution is discussed on the basis of the conclusion obtained in the previous paper.

The ability to predict the adsorbability for a given adsorbent from a knowledge of the physical properties of the adsorbate has long been an important objective in adsorbent-adsorbate interaction research. In gas-phase adsorption, the decisive component of the adsorption forces on an activated carbon surface is the dispersion component of the Van der Waals forces. Therefore, the adsorptive interaction is strongly dependent on the polarizability of the molecules. Since the polarizability of a molecule is approximately proportional to the volume of a molecule or molar volume, the adsorbability can also be evaluated in terms of the molar volume[2)] or the parachors.[3)] Reucroft *et al.*[4)] studied the relationship between the adsorbability and various physical constants and concluded that the molar refraction gives a good correlation. However, no similar investigation in liquid-phase adsorption has been thoroughly undertaken in contrast to that in the gas phase. A brief survey of adsorption from the liquid phase was, though, made by Hassler.[5)] He listed all the factors influencing adsorption at the carbon-liquid interface and noted that such physical properties as the molecular weight and the solubility significantly influenced the adsorbability. The significance of these factors has also been pointed out by numerous other investigators.[6—14)] Pouchly and Vavruch[15)] noted that the main factor was the general rule of the mutual affinity of substances with similar polarities. From this rule, it is expected that nonpolar substances will be more readily adsorbed on activated carbon, a nonpolar adsorbent, than polar substances. Wohleber and Manes[16)] presented a method for estimating the adsorbability of a partially miscible organic liquid from a water solution on an activated carbon by the knowledge of the adsorbability of the vapors of the solute and the solvent. The method, which is based on the Polanyi adsorption potential theory,[17)] suggests that the adsorbability in the liquid phase can be estimated from the molar volume, the parachor, or the molar refraction, which are used as the criteria of adsorbability in the gas phase. Abe *et al.*[18)] reported that the adsorption process of aliphatic monofunctional compounds is energetically similar to the precipitation process of the hydrocarbon portion of the solute. This suggests that the adsorbability can be estimated from the volume of the hydrocarbon portion of the solute. These discussions of the relationship between the adsorbability in the liquid-phase adsorption and the physical constants have been so far done almost always qualitatively, because they are based on limited data for a small number of compounds. Therefore, it is desirable to relate quantitatively the adsorbability to the physical constants for a large number of compounds. Giusti *et al.*[11)] have measured the amounts of adsorption of 90 organic compounds on an activated carbon, but have not discussed the subject thoroughly. Since a good correlation has been obtained between our adsorption data in the previous paper[18)] and Giusti's data, in this paper we have related the adsorbability to the physical constants quantitatively by using both sets of data. Furthermore, in order to find a physical constant with a good correlation with the adsorbability, we have also examined the physical constants which have been used for the prediction of the adsorbability on the other adsorption systems. For example, the inorganicity/organicity value has been used for predicting the affinity of dyes on fibers.[19,20)] The partition coefficient between water and 1-octanol has been used for estimating the affinity of organic compounds in the hydrophobic region in a protein molecule.[21,22)] The molar attraction constant, which gives a quantitative measure of the relative mutual attraction of organic molecules to one another as a result of dispersion forces, has been used as a physicochemical criterion for the sorption at the membrane-solution interface in reverse osmosis.[23)]

In this paper we have examined the correlation between the adsorbabilities of 93 organic compounds and these physical constants for predicting the adsorbability in terms of the physical constant. Furthermore, we have examined whether or not these results can be successfully explained by the adsorptive mechanism proposed in the previous paper.[18)]

TABLE 1. ADSORPTION OF ORGANIC COMPOUNDS FROM AN AQUEOUS SOLUTION ON CAL ACTIVATED CARBON, 25 °C

Compound No.	Compound	$\alpha^{a)}$	$\frac{C_0-C^{b)}}{C}$	$\alpha^{c)}$
	[Alcohols]			
1	Methanol		0.0373	0.0121
2	Ethanol		0.110	0.0445
3	1-Propanol	0.184	0.233	0.110
4	1-Butanol	0.680	1.15	0.755
5	1-Pentanol	2.25	2.55	1.98
6	1-Hexanol	9.08	21.2	25.4
7	2-Propanol		0.144	0.0615
8	2-Propene-1-ol		0.267	0.130
9	2-Methyl-1-propanol		0.721	0.430
10	2-Methyl-2-propanol		0.418	0.223
11	2-Ethyl-1-butanol		5.90	5.43
12	2-Ethyl-1-hexanol		69.0	106
	[Aldehydes]			
13	Formaldehyde		0.101	0.0401
14	Acetaldehyde	0.0561	0.135	0.0569
15	Propionaldehyde	0.151	0.383	0.200
16	Butyraldehyde	0.641	1.12	0.732
17	Valeraldehyde	2.41		
18	Acrylaldehyde		0.441	0.237
19	Crotonaldehyde		0.838	0.516
20	Benzaldehyde		15.7	17.9
21	Paraldehyde		2.83	2.24
	[Amines]			
22	Dipropylamine		4.05	3.44
23	Butylamine		1.08	0.700
24	Dibutylamine		6.69	6.31
25	Allylamine		0.458	0.249
26	Ethylenediamine		0.120	0.0494
27	Diethylenetriamine		0.416	0.221
28	2-Aminoethanol		0.078	0.0292
29	2,2′-Iminodiethanol		0.380	0.199
30	2,2′,2″-Nitrilotriethanol		0.493	0.272
31	2-Amino-1-methylethanol		0.250	0.120
32	1,1′-Dimethyl-2,2′-iminodiethanol		0.842	0.519
	[Pyridines & Morpholines]			
33	Pyridine		0.898	0.560
34	2-Methyl-5-ethylpyridine		8.35	8.26
35	*N*-Methylmorpholine		0.739	0.443
36	*N*-Ethylmorpholine		1.14	0.747
	[Aromatics]			
37	Benzene		18.8	21.7
38	Toluene		3.80	3.20
39	Ethylbenzene		5.39	4.87
40	Phenol		4.15	3.55
41	Hydroquinone		4.99	4.44
42	Aniline		2.98	2.38
43	Styrene		9.00	9.03
44	Nitrobenzene		22.3	27.1
	[Esters]			
45	Methyl acetate	0.274	0.355	0.183
46	Ethyl acetate	0.913	1.02	0.654
47	Propyl acetate	4.24	3.03	2.43
48	Butyl acetate	15.7	5.49	4.98
49	Pentyl acetate		7.28	6.99
50	Isopropyl acetate		2.13	1.59
51	Isobutyl acetate		4.56	3.98
52	Vinyl acetate		1.80	1.30
53	2-Ethoxyethyl acetate		1.92	1.40
54	Ethyl acrylate		3.49	2.88
55	Butyl acrylate		22.3	27.0
	[Ethers]			
56	Diethyl ether	0.548		
57	Dipropyl ether	6.91		
58	Diisopropyl ether		4.04	3.44
	[Glycols & Glycol Ethers]			
59	Ethylene glycol		0.0730	0.0269
60	Diethylene glycol		0.355	0.183
61	Triethylene glycol		1.10	0.716
62	Tetraethylene glycol		1.39	0.949
63	1,2-Propanediol		0.131	0.0549
64	Dipropylene glycol		0.198	0.0905
65	2-Methyl-2,4-pentanediol		1.59	1.12
66	2-Methoxyethanol		0.156	0.0678
67	2-Ethoxyethanol		0.450	0.243
68	2-Butoxyethanol		1.27	0.852
69	2-(Hexyloxy)ethanol		6.74	6.38
70	2-(2-Ethoxyethoxy)-ethanol		0.772	0.468
71	2-(2-Butoxyethoxy)-ethanol		4.78	4.21
72	3,6,9-Trioxaundecan-1-ol		2.30	1.74
	[Halogenated Compounds]			
73	1,2-Dichloroethane		4.29	3.69
74	1,2-Dichloropropane		13.1	14.3
	[Ketones]			
75	Acetone	0.125	0.279	0.137
76	2-Butanone	0.361	0.880	0.547
77	2-Pentanone	1.39	2.28	1.72
78	2-Hexanone	5.13	4.17	3.57
79	4-Methyl-2-pentanone		5.58	5.08
80	5-Methyl-2-hexanone		5.75	5.27
81	Cyclohexanone		2.01	1.48
82	Acetophenone		34.7	46.0
83	Isophorone		28.4	36.1
	[Acids]			
84	Formic acid		0.307	0.153
85	Acetic acid		0.316	0.159
86	Propionic acid	0.230	0.484	0.266
87	Butyric acid	0.813	1.47	1.01
88	Valeric acid	3.84	3.93	3.32
89	Hexanoic acid	16.1	32.3	42.2
90	Acrylic acid		1.82	1.31
91	Benzoic acid		10.2	10.6
	[Oxides]			
92	Propylene oxide		0.353	0.182
93	Styrene oxide		20.3	24.3

a) Our data.[18] b) Giusti's data.[11] c) Calculated from Eq. 2.

Procedure

In a previous paper[18)] the adsorption isotherms of 22 aliphatic monofunctional compounds from an aqueous solution on Pittsburgh Activated Carbon-grade CAL activated carbon have been determined, and the adsorbabilities of the solutes at an infinite dilution have been calculated. The adsorbability (α) has been defined as follows:

$$\alpha \equiv \lim_{C \to 0} \frac{X}{C}, \tag{1}$$

where X is the amount of adsorbed solute on carbon (mg/g) and C is the equilibrium concentration of the solute (mg/l). The constant, α, represents the partition coefficient between the solution and the adsorbed phases at an infinite dilution. The values of α for the 22 compounds are presented in Table 1. Giusti *et al.*[11)] have reported the adsorption data for 90 compounds on Westvaco Nuchar Activated Carbon-grade WV-G activated carbon. They determined the adsorbability for each compound by measuring the amount of adsorption at an equilibrium concentration under the following conditions: a concentration of activated carbon of 5000 mg/l, and an initial concentration of the solute (C_0) of 1000 mg/l. We have calculated the value of $(C_0-C)/C$, which represents the partition coefficient at the equilibrium concentration, C, from their data.

Figure 1 shows the relationship between the value of $\log \alpha$ in our data and the values of $\log\{(C_0-C)/C\}$ calculated from Giusti's data for the common 19 compounds included in both sets of data. It can be seen from Fig. 1 that $\log \alpha$ is related to $\log\{(C_0-C)/C\}$ by the following equation:

$$\log \alpha = 1.21 \log \frac{C_0-C}{C} - 0.195. \tag{2}$$

The correlation coefficient (r) between $\log \alpha$ and $\log\{(C_0-C)/C\}$ obtained by the regression analysis was high, $r=0.957$, in spite of the difference in the carbon used. Assuming that Eq. 2 was applicable to the other 71 compounds, the α values for the 71 compounds were calculated from Eq. 2. These values are also tabulated in Table 1. In this manner, the values of α for all 93 organic compounds were determined.

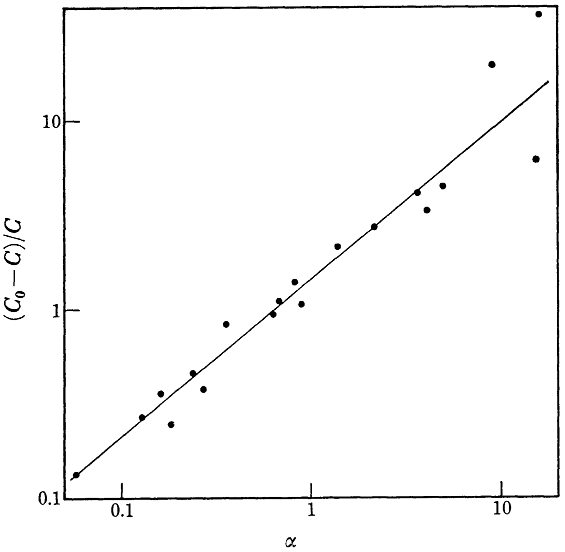

Fig. 1. Relationship between α in our data and $(C_0-C)/C$ calculated from Giusti's data.

The correlation between the adsorbabilities (α) and physical constants (x) were tested by means of the following linear relation:

$$\log \alpha = ax+b, \tag{3}$$

where a and b are constants. By regression analysis, the correlation coefficient (r) and the a and b constants were determined.

Results

Molecular-size Parameters. The relationship between the molecular weight (M) and $\log \alpha$ is given in Fig. 2, while the results of the regression analysis are given in Table 2. The correlation coefficient was very high for the aliphatic monofunctional compounds and for all the aromatics except benzene, but for the aliphatic multifunctional compounds it was low. It can be seen from Table 2 or Fig. 2 that the α value for the aliphatic monofunctional compounds is approximately doubled for each rise of 10 in the molecular weight. As can be seen from Table 2, the correlation coefficient between the molar volume (V) and $\log \alpha$ was also high for aliphatic monofunctional compounds, and the correlation with the carbon number (N) of compound was good for all the compounds.

Aqueous Solubility (C_s). Figure 3 shows the relationship between $\log C_s$ and $\log \alpha$. The correlation

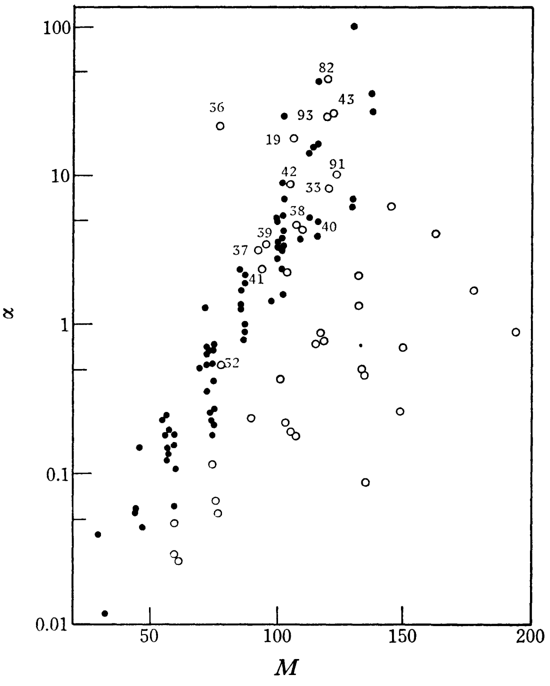

Fig. 2. Relationship between α and molecular weight. ●: Aliphatic monofunctional compounds, ○: aromatics and multifunctional compounds.

TABLE 2. RESULTS OF REGRESSION ANALYSIS FOR THE $\log\alpha = ax + b$ EQUATION

Physical constant	x	Compound	a	b	Number of data points n	Correlation coefficient r
Molecular weight	M	AMF[a]	0.0311	−2.60	73	0.943
		AMF+AR[b]	0.0315	−2.59	87	0.927
		AMF+AR*[c]	0.0317	−2.63	86	0.945
		T[d]	0.0175	−1.62	112	0.628
Molar volume[f]	V	AMF	0.0241	−2.38	59	0.868
		T	0.0206	−2.03	84	0.672
Carbon number	N	AMF	0.417	−1.79	73	0.864
		T	0.368	−1.72	112	0.818
Solubility[g]	$\log C_s$	L[e]	−1.03	0.816	15	−0.962
		AMF	−0.752	0.716	70	−0.842
		T	−0.647	0.656	108	−0.808
Molar-attraction constant	$\sum F$	AMF	0.00364	−3.17	68	0.932
		T	0.00267	−2.42	92	0.745
$\dfrac{\text{Organicity}}{\text{Inorganicity}}$	O/IO	AMF	0.302	−0.401	73	0.464
		T	0.204	−0.294	112	0.455
Modified O/IO value	A	AMF	2.30	−2.04	71	0.944
Partition coefficient (octanol-water system)	$\log P_{oct}$	AMF	0.932	−0.906	50	0.904
		T	0.523	−0.408	77	0.744
Dielectric constant[f]	D	AMF	−0.0495	0.564	55	−0.585
		T	−0.0441	0.577	76	−0.544
Molar refraction[f]	$[R]$	AMF	0.0968	−2.29	61	0.898
		T	0.0924	−2.30	80	0.825
Parachor[f]	$[P]$	AMF	0.0114	−2.51	45	0.889
		T	0.00925	−2.13	64	0.660

a) AMF: Aliphatic monofunctional compounds. b) AR: Aromatics. c) AR*: Aromatics except benzene. d) T: AMF+AR+Aliphatic multifunctional compounds. e) L: AMF in our work. f) These physical constants are cited from J. A. Riddick and W. B. Bunger, "Organic Solvents," Wiley-Interscience, New York (1970). g) Reference (f) and "International Critical Tables," McGraw-Hill, New York (1933).

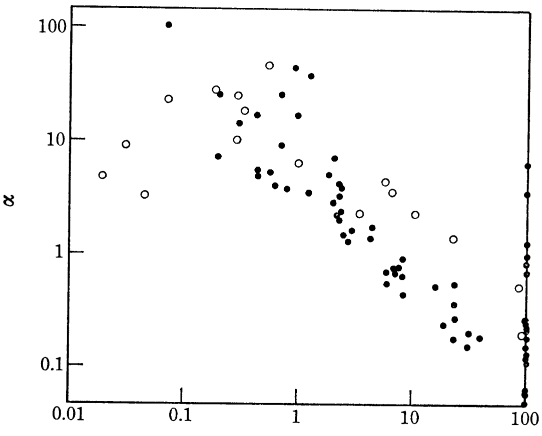

Fig. 3. Relationship between α and aqueous solubility.

coefficient was very high for the 15 linear aliphatic monofunctional compounds in our work. The value of a for these compounds was about −1, which suggests the following relationship;

$$\alpha \cdot C_s = \text{const.} \tag{4}$$

However, the correlation coefficient for all aliphatic monofunctional compounds was low because the compounds with 100 weight % aqueous solubility revealed a wide range of adsorbability.

Molar-attraction Constant (F). The concept of the cohesive energy of a liquid has been discussed extensively in the literature.[24,25] The molar cohesive energy, E, is given by this expression:

$$E \fallingdotseq \Delta H - RT \tag{5}$$

where ΔH is the heat of vaporization; R, the gas constant, and T, the absolute temperature. When the cohesion between molecules is due to dispersion forces, as is essentially the case with nonpolar molecules, E is related to the heat of mixing per cc (ΔH_{cc}) by Scatchard's[26] semi-empirical relation:

$$\Delta H_{cc} = \phi_1\phi_2\{(E_1/V_1)^{1/2} - (E_2/V_2)^{1/2}\}^2, \tag{6}$$

where ϕ is the volume ratio and the subscripts 1 and 2 represent a set of two dissimilar molecules. Equation 6 is equivalent to the statement that the cohesive energy, E, of a mixture of n_1 mol of Liquid 1 and n_2 mol of Liquid 2 can be given by this expression:

$$E^{1/2}(n_1V_1 + n_2V_2)^{1/2} = n_1(E_1V_1)^{1/2} + n_2(E_2V_2)^{1/2}, \tag{7}$$

which shows that $(EV)^{1/2}$ is an additive property. Assuming that this property might hold for the atoms

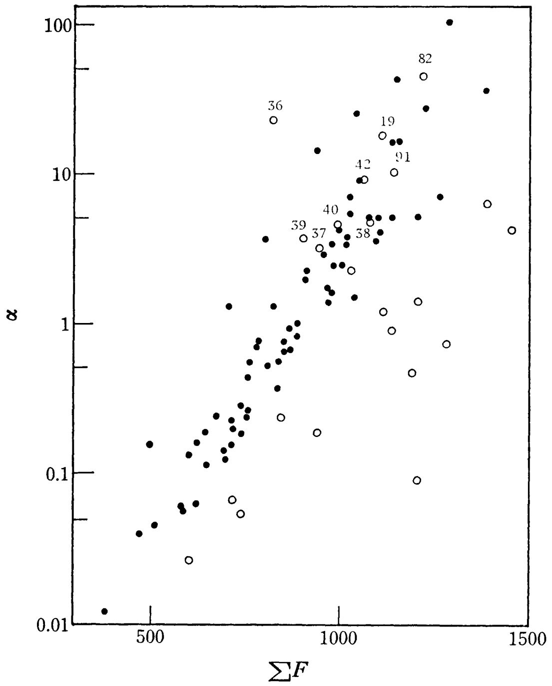

Fig. 4. Relationship between α and molar-attraction constant.

or groups constituting a molecule, Small[24] derived a set of additive constants for the common groups of organic molecules. These constants are called molar-attraction constants and are denoted by the symbol *F*. Then, $\sum F$ summed over the present groups gives the value of $(EV)^{1/2}$ for 1 mol of the substance concerned.

Figure 4 shows the relationship between the $\sum F$ values calculated from Small's *F* values for the compounds in Table 1 and log α. The correlation for the aliphatic monofunctional compounds and aromatics except benzene was very high, while that for aliphatic multifunctional compounds was low. This tendency is analogous to that of the molecular weight.

Organicity and Inorganicity. In order to estimate the solubility of organic compounds, Fujita[27] proposed the concept of organicity and inorganicity, where it is assumed that the organicity value per carbon atom is 20 and that inorganicity value for a hydroxyl group is 100. The inorganicity values for the other functional groups are determined in values relative to that for the hydroxyl group; they are given in Table 3. Since the organicity/inorganicity value (*O*/*IO*) is a criterion of the solubility, the value can also be used as a criterion of adsorbability. There existed a linear relationsihp between *O*/*IO* and log α for a homologous series of solutes, but the correlation coefficient for all the compounds in Table 1 was very low. This suggests that Fujita's *IO* value cannot be used as a criterion of adsorbability. In order to improve the correlation between the *O*/*IO* value and log α, the *IO* values for the functional groups were redetermined so as to fit the *O*/*IO* *vs.* log α plots of all the compounds to the straight line obtained for alcohols. These values are given in Table 3. Figure 5 shows the relationship between log α and the modified *O*/*IO* values calculated from the redetermined *IO* values and Fujita's *O* values. The correlation coefficient was very high for aliphatic monofunctional compounds.

Table 3. Inorganicity values for functional groups

Functional group		Inorganicity value	
		Fujita[10]	This work
Alcohols	-OH	100	100
Carboxylic aicds	-COOH	150	93
Ketones	>CO	65	109
Ethers	-O-	20	103
Esters	-COOR	60	93
Aldehydes	-CHO	65	98

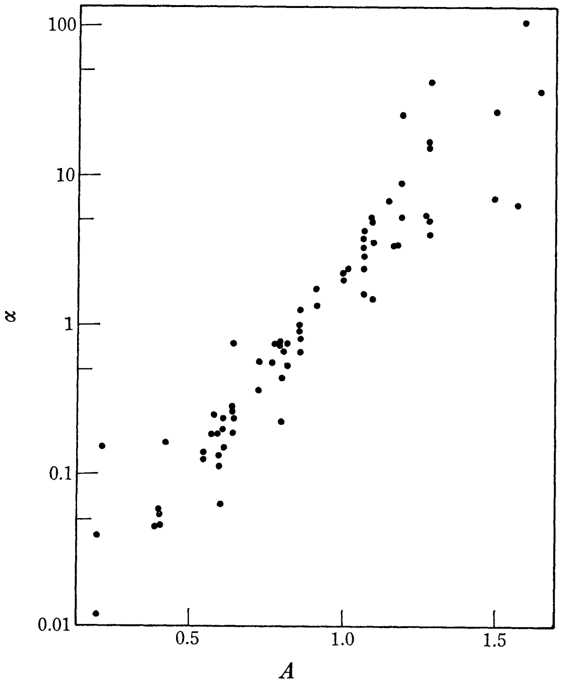

Fig. 5. Relationship between α and modified organicity/inorganicity.

Partition Coefficient between Water and 1-Octanol (P_{oct}). Assuming that the adsorption process is identical with the partition process between water and adsorbed phases, and that the polarity of the adsorbed phase is similar to that of 1-octanol, a high correlation between P_{oct} and α can be expected. Figure 6 shows the relationship between the log P_{oct} values calculated from Hansch's data[28] and log α. The correlation coefficient was high for aliphatic monofunctional compounds.

Polarity Parameters. The following empirical polarity parameters of organic compounds, among others, have been proposed by earlier investigators: $(D-1)/(2D+1)$ (*D*: dielectric constant, Kirkwood[29]), the E_T-values (Dimroth, Reichardt[30]), the *Y*-values (Winstein, Grunwald[31]), the Ω-values (Berson, Hamlet, Mueller[32]), the *Z*-values (Kosower[33]), and the *S*-values (Brownstein[34]). The relationship between the polarity parameters and log α were all similar in tendency, and the correlation coefficients were low.

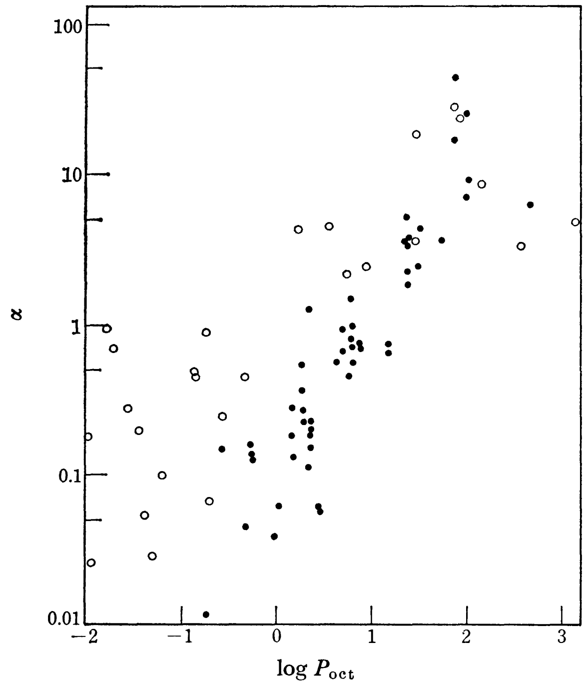

Fig. 6. Relationship between α and partition coefficient.

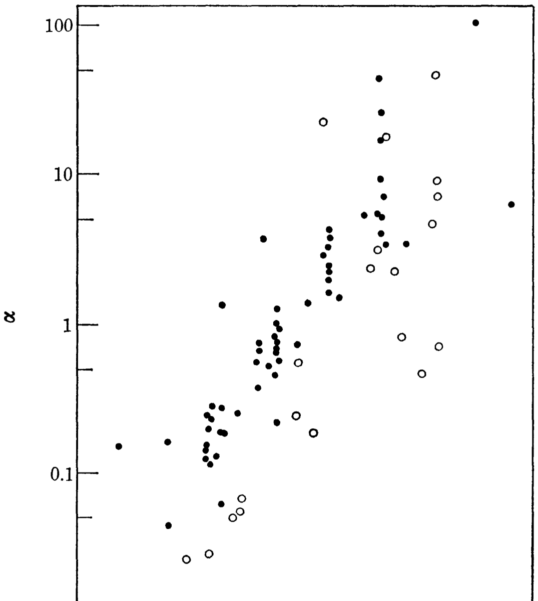

Fig. 7. Relationship between α and molar refraction.

Molar Refraction (*[R]*). The molar refraction is obtained from the Lorenz-Lorentz equation using the following form:

$$[R] = \frac{n^2-1}{n^2+2}\frac{M}{\rho} \tag{8}$$

where n is the refractive index and ρ is the density. Figure 7 shows the relationship between $[R]$ and log α. The correlation coefficient for the 61 aliphatic monofunctional compounds was 0.898. In gas-phase adsorption, Reucroft *et al.*,[4] obtained the high correlation coefficient of 0.94 for 15 organic vapors.

Parachor (*[P]*). Parachor is obtained approximately by the use of the following equation:

$$[P] = \frac{M}{\rho}\cdot\gamma^{1/4} \tag{9}$$

where γ is the surface tension. It can be seen from Table 2 that the correlation coefficient between $[P]$ and log α is high, 0.889, for 45 aliphatic monofunctional compounds. In gas-phase adsorption, the value was 0.90 for 15 organic vapors.[4]

Discussion

In this work, the relationship between the adsorbability and various physical constants was examined for a large number of organic compounds, and it was found that, for aliphatic monofunctional compounds, there existed a good linear relationship between log α and the following physical constants: the molecular weight, the molar-attraction constant, and the modified *O*/*IO* value. This indicates that these physical constants are useful for predicting the adsorbability of aliphatic monofunctional compounds on activated carbon from an aqueous solution and that the *a* and *b* constants in Eq. 3 are useful for characterizing the adsorptive power of activated carbon. If the *a* and *b* constants are determined from the adsorption data of several compounds, the adsorbability for many other compounds can be predicted from only the physical constant. On the other hand, the adsorbability of multifunctional compounds could not be predicted from the physical constant and Eq. 3. The possibility of the prediction for aromatic compounds could not be ascertained because of the small number of compounds studied.

We will now consider the adsorptive mechanism on activated carbon in the water phase. In a previous paper[18] the free energy change of the adsorption process of 22 aliphatic monofunctional compounds on CAL activated carbon from aqueous solution was compared with the free energy of the precipitation process of the same compound from water to the pure liquid solute; the following results were obtained. 1) The adsorption process of the hydrocarbon portion of a solute molecule is analogous to the precipitation process of the portion. 2) The functional group situated in the terminal position of a solute molecule is appreciably hydrated, even in the adsorbed phase. 3) The functional group situated inside a solute molecule is not appreciably hydrated in the adsorbed phase. These results suggest that the adsorption of the solute takes place by means of the precipitation of the hydrocarbon portion of the solute from the aqueous solution and that the adsorbability depends mainly on the volume of the hydrocarbon. Since the free energy change for the precipitation process of the hydrocarbon is negative, the adsorbability increases with an increase in the volume of the hydrocarbon portion in a solute molecule. The fact that, for aliphatic monofunctional compounds, a high correlation coefficient was obtained between the adsorbability and the molecular weight, the molar volume, and the modified *O*/*IO* value can be explained by the fact that the increase in these physical constants is approximately equal to the increase in the volume of the hydrocabon portion of a solute molecule. The high correlation with the molar-attraction constant, the molar refraction, and the parachor can also be accounted for by the fact that these physical constants are functions of the molar volume. Furthermore, the result that the correlation coefficient with the carbon atom number was high in spite of the variety of compounds suggests that the volume of the hydrocarbon was a dominant factor governing the adsorption. It can be seen from the modified *IO* values in Table 3 that the adsorbability does not appreciably depend on the kind of functional group.

The adsorbability of the multifunctional compounds was lower than that of the monofunctional compounds. This result can be explained by the facts that the functional group situated inside a solute molecule is somewhat dehydrated in the adsorbed phase and that the free energy change for the dehydration of the functional group is positive. In addition, the somewhat hydrated functional group may be considered to interfere with the dehydration of the adjacent hydrocarbon portion.

The low correlation with the polarity parameters suggests that the polarity is not the principal factor controlling the adsorbability on activated carbon and that the volume of the hydrocarbon portion of a solute molecule is not the principal factor controlling the polarity. Actually, the polarity is greatly influenced by the functional group.

Although, in this paper, we did not discuss the influence of the difference in activated carbon on the adsorbability of organic compounds, in a subsequent investigation[35)] we obtained a similar result for a large number of activated carbons. It should be remembered, however, that surface oxides influence the adsorption of organic compounds.[5,7,11,36,37)] In particular, the adsorption of strongly ionized low-molecular-weight compounds may be greatly influenced by surface oxides in a low or high pH solution.

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References

1) Part II: I. Abe, K. Hayashi, M. Kitagawa, and T. Urahata, *Nippon Kagaku Kaishi*, **1979**, 830.

2) M. M. Dubinin and D. P. Timofeyev, *Zh. Fiz. Khim.*, **22**, 133 (1948).

3) B. A. Vaskovsky; see M. M. Dubinin and E. D. Zaverina, *Dokl. Akad. Nauk SSSR*, **72**, 319 (1950).

4) P. J. Reucroft, W. H. Simpson, and L. A. Jonas, *J. Phys. Chem.*, **75**, 3526 (1971).

5) J. W. Hassler, "Activated Carbon," Chemical Publishing Company, New York (1963).

6) A. S. Weatherburn, G. R. F. Rose, and C. H. Bayley, *Can. J. Res.*, **27F**, 179 (1949).

7) J. S. Mattson and H. B. Mark, Jr., "Activated Carbon," Marcel Dekker, New York (1971).

8) M. Komori, K. Urano, and T. Nakai, *Nippon Kagaku Kaishi*, **1974**, 1795.

9) K. Urano, Y. Nishimura, and Y. Yanaga, *Nippon Kagaku Kaishi*, **1975**, 1444.

10) I. Abe, K. Hayashi, M. Kitagawa, and T. Urahata, *Nippon Kagaku, Kaishi*, **1978**, 1188.

11) D. M. Giusti, R. A. Conway, and C. T. Lawson, *J. Water Pollut. Control Fed.*, **46**, 947 (1974).

12) W. J. Weber, Jr., and J. C. Morris, *J. Sanit. Eng. Div.*, **89**, **SA2**, 31 (1963).

13) W. J. Weber, Jr., and J. C. Morris, *J. Sanit. Eng. Div.*, **90**, **SA3**, 79 (1964).

14) R. Lemieux and J. Morrison, *Can. J. Res.*, **25B**, 212 (1947).

15) J. Pouchly and I. Vavruch, "Physical Chemistry of Colloid Systems," SNTL, Prague (1960).

16) D. A. Wohleber and M. Manes, *J. Phys. Chem.*, **75**, 61 (1971).

17) M. Polanyi, *Verh. Deut. Phys. Ges.*, **16**, 1012 (1914); **18**, 55 (1916); *Z. Elektrochem.*, **26**, 370 (1920); *Z. Phys.*, **2**, 111 (1920).

18) I. Abe, K. Hayashi, M. Kitagawa, and T. Urahata, *Bull. Chem. Soc. Jpn.*, **52**, 1899 (1979).

19) N. Kuroki, "Senshoku Riron Kagaku," Maki-shoten, Tokyo (1969).

20) Z. Yoshida, S. Sagawa, and R. Oda, *Kogyo Kagaku Zasshi*, **63**, 305 (1960).

21) C. Hansch, K. Kiehs, and G. L. Lawrence, *J. Am. Chem. Soc.*, **87**, 5770 (1965).

22) K. Kiehs, C. Hansch, and L. Moore, *Biochemistry*, **5**, 2602 (1966).

23) "Reverse-Osmosis and Synthetic Membranes," ed by S. Sourirajan, National Research Council, Canada (1977), Chap. 2.

24) P. A. Small, *J. Appl. Chem.*, **3**, 71 (1953).

25) J. H. Hilderband, J. M. Prausnitz, and P. L. Scott, "Regular and Related Solutions," Van Nostrand Reinhold, New York (1970).

26) G. Scatchard, *Chem. Rev.*, **44**, 7 (1949).

27) A. Fujita, *Pharm. Bull. (Tokyo)*, **2**, 163 (1954).

28) A. Leo, C. Hansch, and D. Elkins, *Chem. Rev.*, **71**, 525 (1971).

29) J. G. Kirkwood, *J. Chem. Phys.*, **2**, 351 (1934).

30) K. Dimroth and C. Reichardt, "Palette," Publication of Sandoz AG., Basel, Switzerland (1962), No. 11, p. 28.

31) E. Grunwald and S. Winstein, *J. Am. Chem. Soc.*, **70**, 846 (1948).

32) A. Berson, Z. Hamlet, and W. A. Mueller, *J. Am. Chem. Soc.*, **84**, 297 (1962).

33) E. M. Kosower, *J. Am. Chem. Soc.*, **80**, 3253 (1958).

34) S. Brownstein, *Can. J. Chem.*, **38**, 1590 (1960).

35) I. Abe, K. Hayashi, M. Kitagawa, and T. Urahata, *Nippon Kagaku Kaishi*, **1930**, 545.

36) M. V. C. Sastri, *Indian Inst. Sci.*, *Quart. J.*, **5**, 145, 162 (1942).

37) I. Abe, K. Hayashi, and M. Kitagawa, *Yukagaku*, **26**, 355 (1977).