Interaction of a Group of Weak Organic Acids and Phenols with a Polyamide

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A drug–plastic sorption study was conducted using six compounds of interest to pharmaceutical and medical scientists. The compounds studied were (a) benzoic acid, (b) salicylic acid, (c) p-hydroxybenzoic acid, (d) methyl p-hydroxybenzoate, (e) propyl p-hydroxybenzoate, and (f) butyl p-hydroxybenzoate, while the plastic material was an insoluble polyamide (nylon-6). Sorption and diffusion experiments were conducted at several original concentrations and at three different temperatures, from which it was possible to calculate a number of constants for each agent. Evaluation of the various constants indicated that drug–plastic interactions were due to hydrogen bonding of the agents to the polyamide, but that secondary valence forces of van der Waals type most likely play a predominate role in the interaction or binding mechanism for the more hydrophobic molecules studied. The apparent diffusion coefficients were of the order of 10^{-8} cm.^{2}/sec., while activation energies of diffusion fell within a range of 13.2 Kcal./mole for benzoic acid to 15.5 Kcal./mole for butyl p-hydroxybenzoate. Permeation constants had values approaching 10^{-7} cm.^{2}/sec.

I N THE PAST this laboratory has reported the interaction of a number of weak organic acids or compounds acting as weak organic acids with several insoluble polyamides (1–5). This report is a continuation of these studies. Six compounds and one specific polyamide[1] were employed in this specific study. Sorption and permeation experiments were conducted on all the compounds at several concentrations and at several temperatures. The data permitted the evaluation of a number of constants, both of a thermodynamic and kinetic nature which in turn helped to propose the mechanism of interaction.

EXPERIMENTAL

Equipment and Supplies.—A Beckman DB spectrophotometer (Beckman Instruments, Inc., Fullerton, Calif.), benzoic acid (A. R., J. T. Baker Chemical Co., Phillipsburg, N. J.), salicylic acid (A. R., Mallinckrodt Chemical Works, St. Louis, Mo.), p-hydroxybenzoic acid (A. R., Eastman Organic Chemicals, Rochester, N. Y.), methyl p-hydroxybenzoate (A. R., Eastman Organic Chemicals, Rochester, N. Y.), propyl p-hydroxybenzoate (A. R., Eastman Organic Chemicals, Rochester, N. Y.), butyl p-hydroxybenzoate (A. R., Eastman Organic Chemicals, Rochester, N. Y.), and nylon-6[2] were employed.

Method of Analysis of Solutions.—The assay for each compound was based upon a spectrophotometric method, using enough diluent to give a final

concentration of solute in the range of 2×10^{-3} mg./ml. to 6×10^{-3} mg./ml. for spectrophotometric examination. The absorbance was determined at the optimum wavelength for each compound, using matched 1-cm. silica cells as the sample and reference holders. Table I presents the wavelength of maximum absorbance and diluting vehicle for each compound.

Equilibrium Sorption Studies.—Solutions of benzoic, salicylic, and p-hydroxybenzoic acid, as well as methyl p-hydroxybenzoate, were prepared in five concentrations, ranging from 0.05 to 0.025%.[3] Due to limited solubility in water, five concentrations of propyl- and butyl p-hydroxybenzoate were made in ranges of 0.005 to 0.025%. In all cases, freshly prepared distilled water was utilized as the solvent medium.

Exactly 100 ml. of each solution was pipeted into specially constructed cylindrical glass tubes, measuring 12 in. in length and 1.5 in. in diameter. The tubes were fitted with ground glass stoppers, attached by metal or rubber springs, allowing for total immersion into a water bath at the desired temperature. After a period of time, adequate for equilibrium temperature to be reached in the tubes, the tubes were lifted from the bath, and strips of polyamide (accurately weighed to a total of 2 Gm.) were placed into each tube. The tubes were once again stoppered and carefully placed back into the water bath. Determinations of solute concentrations were made on each solution after sufficient time (approximately 14 days) had elapsed to ensure that equilibrium had been reached. Since blank solutions, exposed to similar temperatures, showed no loss of solute for the time period under consideration, any loss of solute in the test solutions was assumed to have been sorbed by the polyamide. These experiments were conducted at three different temperatures ($50 \pm 0.02°$, $60 \pm 0.02°$, and $70 \pm 0.02°$).

The data obtained from these sorption experiments were then treated to determine the solubility coefficient or distribution ratio for each individual compound in the polyamide at the various temperatures under consideration. This solubility coeffi-

TABLE I.—WAVELENGTH OF MAXIMUM ABSORPTION

Compd.	Diluent	Optimum Wavelength, mμ
Benzoic acid	0.1 N HCl	230
Salicylic acid	0.1 N HCl	236
p-Hydroxybenzoic acid	0.1 N HCl	255
Methyl p-hydroxybenzoate	Distilled water	255
Propyl p-hydroxybenzoate	Distilled water	255
Butyl p-hydroxybenzoate	Distilled water	255

TABLE II.—SOLUBILITY COEFFICIENTS OF COMPOUNDS IN POLYAMIDE AT THREE TEMPERATURES

Compd.	S (moles/Kg./moles/L.) 50°	60°	70°
Benzoic acid	19.08	15.51	12.97
Salicylic acid	33.23	26.81	19.97
p-Hydroxybenzoic acid	19.44	15.96	12.65
Methyl p-hydroxybenzoate	25.29	21.74	18.04
Propyl p-hydroxybenzoate	88.23	77.63	72.95
Butyl p-hydroxybenzoate	93.17	87.98	80.90

cient was evaluated by the use of the following equation:

$$S = C_s/C_L \qquad \text{(Eq. 1)}$$

where S is the solubility coefficient relating the quantity of solute in the solid phase to the quantity of solute in the liquid phase; C_s is the equilibrium concentration of solute in the solid phase (nylon) in moles/Kg.; and C_L is the equilibrium concentration of solute in the liquid phase in moles/L. By plotting values of C_s against the corresponding values for C_L, a linear relation resulted for all the compounds at the three temperatures. From the slopes, the solubility coefficients were deduced. Table II presents the calculated C_s/C_L or solubility coefficients for the six compounds at each of the temperatures studied.

Standard Affinity, Heat of Sorption, and Entropy of Sorption.—To gain an insight into the attraction forces between the various compounds and the polyamide, standard affinities ($-\Delta\mu°$) were calculated by the use of the expression:

$$-\Delta\mu° = RT \ln S \qquad \text{(Eq. 2)}$$

where S is the equilibrium sorption constant and is equal to the solubility coefficient depicted in Eq. 1 while R and T are the usual gas constant and absolute temperatures, respectively. Table III includes the standard affinities for all the compounds at each of the three temperatures.

In a relatively narrow temperature range, the standard affinity is related to the standard heat of sorption ($\Delta H°$) through the equation shown below:

$$\Delta\mu°/T = \Delta H°/T + C \qquad \text{(Eq. 3)}$$

where all the terms are as previously defined, while C stands for a constant of integration. From the slope of the line, the heat of sorption may be calculated. Calculated values for the heats of sorption for each of the compounds are found in Table III.

Since the standard affinity, $\Delta\mu°$, may be considered as a change in free energy as the solute migrates from the solution to the solid phase (nylon), and $\Delta H°$ represents the heat of sorption or enthalpy, it follows that the entropy ($\Delta S°$) of sorption may be evaluated through the thermodynamic relationship:

$$\Delta\mu° = \Delta H° - T\Delta S° \qquad \text{(Eq. 4)}$$

The entropy values have also been included in Table III.

Permeation and Diffusion Studies.—Since the sorption process of dyes and other agents in nylon is governed primarily by the diffusion step in the substrate, experiments were conducted to evaluate the apparent diffusion coefficient and permeability constant for each compound at the three temperatures given earlier and at a number of original concentrations.

Solutions of benzoic, salicylic, and p-hydroxy-

TABLE III.—STANDARD AFFINITIES ($\Delta\mu°$), STANDARD HEATS OF SORPTION ($\Delta H°$), AND STANDARD ENTROPIES OF SORPTION ($\Delta S°$) FOR A GROUP OF COMPOUNDS *Via* EQUILIBRIUM SORPTION STUDIES

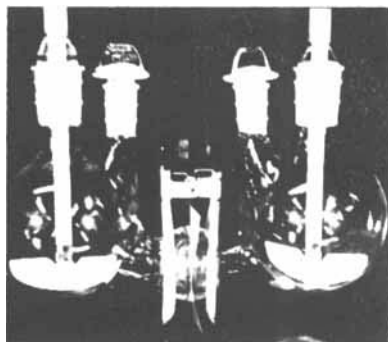| Temp.	$-\Delta\mu°$ (Kcal./mole)	$\Delta H°$ (Kcal./mole)	$\Delta S°$ (cal./mole °)
		Benzoic Acid	
50	1.89		
60	1.81		
70	1.75		
		−4.26	−7.33
		Salicylic Acid	
50	2.25		
60	2.18		
70	2.04		
		−5.60	−10.3
		p-Hydroxybenzoic Acid	
50	1.90		
60	1.83		
70	1.73		
		−4.74	−8.77
		Methyl p-Hydroxybenzoate	
50	2.07		
60	2.04		
70	1.97		
		−3.72	−5.08
		Propyl p-Hydroxybenzoate	
50	2.88		
60	2.88		
70	2.92		
		−2.11	+2.36
		Butyl p-Hydroxybenzoate	
50	2.91		
60	2.96		
70	2.99		
		−1.56	+4.19

Fig. 1.—Photograph showing permeation cell with plastic film dividing the two chambers.

benzoic acids and methyl p-hydroxybenzoate were prepared in three concentrations ranging from 0.10 to 0.30%.

Through the use of a specially designed permeation cell, as shown in Fig. 1, permeation and diffusion studies were conducted in the following manner. Since the cell was composed of two separate flasks, divided by a square of polyamide (approximately 4 in. square with a thickness of 0.010 in.), exactly 500 ml. of the solution under investigation was added to one flask, simultaneously with the addition of an equal volume of distilled water to the other flask. The cell was then lowered into the water bath, and the stirring sleeves connected to an external power source to apply a constant rate of agitation in each flask. At periodic time intervals, aliquots of equal volume were removed from each flask, and set aside until they had reached room temperature. Spectrophotometric assays were made on those samples taken from the flask originally containing only distilled water, to determine the quantity of solute transversing the film barrier. Since the amount of solute passing through the film during the initial portions of the experiment was insignificant in comparison to the amount originally present in the high-concentration side, no assays were made of samples taken from this side of the cell. Sample withdrawal was continued until a steady state transmission was well established, with equal quantities of solute entering the low concentration flask per unit time.

Figure 2 demonstrates the permeation of p-hydroxybenzoic acid through the polyamide as a function of time. By plotting the total amount of solute permeating the nylon barrier against time, it is noted that following a short build-up period, a steady state of transmission is reached. The slope of the line representing the attainment of the steady state was then calculated by the method of least squares, and converted into units of moles of solute entering the flask/sec., so that the permeability constant could be obtained through the use of:

$$P = C/t \cdot LV/CA \qquad \text{(Eq. 5)}$$

where C/t is the slope of the linear portion of the permeation plot in moles/sec.; L is the thickness of the film barrier in cm.; V is the total volume under consideration in cm.^{3}; C is the initial concentration of the solution in moles per total volume;

and A is the surface area of the nylon barrier through which the solute is permeating in cm.^{2}. Through the cancellation of terms, P, the permeability constant is reduced to the units of cm.^{2}/sec.

From the same figure it is possible to evaluate the apparent diffusion coefficient by use of the time-lag equation of Barrer (6), given as:

$$D = L^2/6\tau \qquad \text{(Eq. 6)}$$

where D is the apparent diffusion coefficient in cm.^{2}/sec., L is the thickness of the film in cm., and τ is the time-lag intercept obtained by extrapolation of the steady state slope to the time axis of the permeation plot, converted into seconds.

Table IV presents the values for the apparent diffusion coefficients and the permeability coefficients for all six compounds investigated in the study, at each of the three concentrations and temperatures involved.

Activation Energies of Diffusion and Permeation.—In all compounds studied, it was noted that the rates of diffusion and permeation were temperature dependent. This temperature dependence may be quantitatively expressed by determining the activation energies of diffusion and permeation and can be evaluated through the following equation:

$$\log D = \log D_0 - \Delta E_D/2.303 \, RT \qquad \text{(Eq. 7)}$$

where D is the diffusion coefficient, ΔE_D the activation energy, and R and T the usual constants. A similar expression for permeation may be used to evaluate the activation energy of permeation (ΔE_P). Plots of $\log D$ versus $1/T$ or $\log P$ versus $1/T$ for each of the compounds gave linear relationships from which the activation energies were calculated. These values are shown in Table V.

Thermodynamic Constants from Kinetic Experiments.—Barrer (6) was able to show that the permeability constant and the apparent diffusion coefficient are related by the following expression:
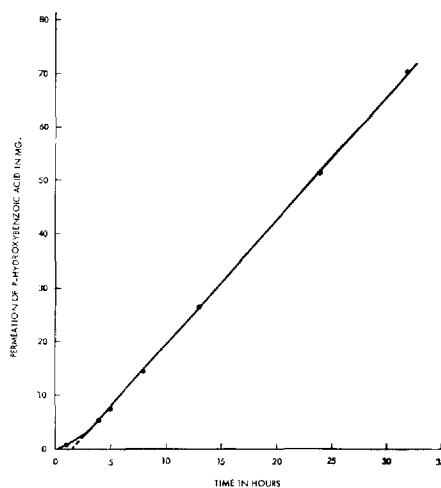
$$S = P/D \qquad \text{(Eq. 8)}$$

Fig. 2.—A plot of the concentration of p-hydroxybenzoic acid permeating through polyamide film vs. time.

where P is the permeability constant expressed in cm.²/sec.; D is the apparent diffusion coefficient in similar units; and S is defined as the solubility coefficient.

TABLE IV.—DIFFUSION COEFFICIENTS AND PERMEABILITY CONSTANTS FOR A GROUP OF WEAK ORGANIC ACIDS AND PHENOLS AT THREE TEMPERATURES (POLYAMIDE)

Temp., °C.	Original % Concn.	$D \times 10^8$, cm.²/sec.	$P \times 10^7$, cm.²/sec.
	Benzoic Acid		
50	0.30	0.546	1.08
60	0.30	1.18	1.83
70	0.30	2.03	2.64
50	0.20	0.689	1.15
60	0.20	1.19	1.65
70	0.20	2.20	2.64
50	0.10	0.750	1.00
60	0.10	1.29	1.45
70	0.10	2.27	2.21
	Salicylic Acid		
50	0.30	0.520	1.54
60	0.30	0.961	2.29
70	0.30	1.76	3.44
50	0.20	0.374	1.25
60	0.20	0.771	1.94
70	0.20	1.58	3.22
50	0.10	0.264	1.02
60	0.10	0.618	1.65
70	0.10	1.43	3.02
	p-Hydroxybenzoic Acid		
50	0.30	0.452	0.933
60	0.30	0.855	1.35
70	0.30	1.87	2.46
50	0.20	0.483	0.919
60	0.20	1.03	1.48
70	0.20	2.01	2.31
50	0.10	0.522	0.906
60	0.10	1.15	1.43
70	0.10	2.30	2.15
	Methyl p-Hydroxybenzoate		
50	0.30	0.579	1.38
60	0.30	1.12	2.31
70	0.30	2.00	3.45
50	0.20	0.551	1.35
60	0.20	1.07	2.29
70	0.20	1.89	3.40
50	0.10	0.521	1.33
60	0.10	1.01	2.26
70	0.10	1.81	3.35
	Propyl p-Hydroxybenzoate		
50	0.03	0.371	3.12
60	0.03	0.756	5.61
70	0.03	1.40	9.34
50	0.02	0.362	3.12
60	0.02	0.718	5.56
70	0.02	1.30	9.16
50	0.01	0.354	3.09
60	0.01	0.703	5.48
70	0.01	1.21	8.98
	Butyl p-Hydroxybenzoate		
50	0.03	0.304	2.66
60	0.03	0.648	5.40
70	0.03	1.31	9.19
50	0.02	0.298	2.64
60	0.02	0.616	5.35
70	0.02	1.22	8.99
50	0.01	0.288	2.63
60	0.01	0.586	5.10
70	0.01	1.12	8.84

TABLE V.—ACTIVATION ENERGIES OF DIFFUSION AND PERMEATION FOR A GROUP OF WEAK ORGANIC ACIDS AND PHENOLS IN THE POLYAMIDE FILM

Compd.	ΔE_D (Kcal./mole)	ΔE_P (Kcal./mole)
Benzoic acid	13.2	9.22
Salicylic acid	16.3	10.4
p-Hydroxybenzoic acid	15.9	10.1
Methyl p-hydroxybenzoate	13.6	10.2
Propyl p-hydroxybenzoate	14.1	11.9
Butyl p-hydroxybenzoate	15.5	13.5

Values for the solubility coefficient, S, were obtained using Eq. 8, and were seen to closely approximate values for this constant obtained by equilibrium sorption studies and calculated by Eq. 1. Using solubility coefficients obtained through permeation and diffusion studies, it was then possible to calculate the standard affinity through Eq. 2, the standard heat of sorption *via* Eq. 3, and with Eq. 4 the standard entropy of sorption.

Table VI presents these thermodynamic constants derived from permeation and diffusion studies; generally, close correlation is seen to those in Table III obtained by equilibrium sorption studies.

DISCUSSION

Equilibrium Sorption Studies.—Examination of Table II in which the solubility coefficients for the six compounds in the polyamide are given, reveals that benzoic acid, salicylic acid, and p-hydroxybenzoic acid have similar values with salicylic acid being somewhat more soluble in the polyamide. Upon esterification of the carboxyl group of p-hydroxybenzoic acid, solubility of the compounds in the nylon phase is seen to increase markedly as the hydrophobic nature of the ester is increased.

With all compounds, and more prominently with the weak organic acids, it was noted as the temperature increased, the solubility coefficients were reduced. This would seem to suggest that the binding process between the nylon and these solutes was temperature dependent, with increased temperature serving to hinder solute-plastic binding.

Standard Affinity, Heat of Sorption, and Entropy of Sorption.—Standard affinity may be considered as being the ability of a particular substrate to attract and hold solute molecules, and is mathematically dependent upon the distribution of solute in the solid and liquid phases at equilibrium, as depicted in Eq. 2.

As seen in Table III, in most cases the standard affinity decreases with increased temperature, thus paralleling what has been shown for dyes and other weak organic acids (7). With the higher molecular weight esters of p-hydroxybenzoic acid, however, this effect is not noted, since the mechanism of interaction of these solutes is not so temperature dependent as with the weak organic acids.

An examination of the standard heats of sorption and standard entropies of sorption for these solutes sorbed by the polyamide (Table III) leads to several suggestions concerning the mechanisms of interaction.

In regard to benzoic, salicylic, and p-hydroxy-

benzoic acids, and methyl *p*-hydroxybenzoate, it is seen that the standard heats of sorption range from −3.7 to −5.6 Kcal./mole. Since the energy requirement for hydrogen-bond formation is considered to be from −4 to −6 Kcal./mole, these experimental values indicate, at least on an energy requirement basis, the formation of a hydrogen bond between these solutes and the polyamide. Presumably, bonding in the case of the weak organic acids would occur between the carboxyl group of the acid and the amide linkages in the nylon chains. Due to the presence of a phenolic hydroxyl group in methyl *p*-hydroxybenzoate, bonding would likely occur between this moiety and the amide linkages in the nylon. Heats of sorption for the propyl and butyl esters of *p*-hydroxybenzoic acid are −2.1 and −1.6 Kcal./mole, respectively, thus leading to the assumption of weak secondary valence forces as being responsible for the binding process between these compounds and the polyamide.

A consideration of the experimental values for the standard entropies of sorption for these compounds may shed further light upon the binding processes.

The concept of entropy as related to drug–plastic interactions encompasses two realms of reasoning. One trend of thought is to consider entropy as being indicative of the probability of a combination occurring between solute and substrate. The greater the increase in entropy, or entropy of sorption, the greater will be the probability of combination between the interactants. Table III reveals that the entropy of sorption is increasing in the cases of the propyl and butyl esters of *p*-hydroxybenzoic acid, while this increase is not noted with

TABLE VI.—THERMODYNAMIC CONSTANTS FROM PERMEATION AND DIFFUSION STUDIES

Temp., °C.	S^a	$-\Delta\mu^{\circ b}$	$\Delta H^{\circ c}$	$\Delta S^{\circ d}$
		Benzoic Acid		
70	11.58	1.66		
60	13.51	1.72	−3.93	−6.61
50	16.63	1.80		
		Salicylic Acid		
70	20.33	2.05		
60	25.21	2.14	−5.60	−10.3
50	33.93	2.26		
		p-Hydroxybenzoic Acid		
70	11.33	1.65		
60	14.17	1.75	−4.78	−9.06
50	19.00	1.89		
		Methyl *p*-Hydroxybenzoate		
70	17.95	1.97		
60	21.48	2.03	−3.46	−4.32
50	24.56	2.05		
		Propyl *p*-Hydroxybenzoate		
70	70.47	2.90		
60	76.56	2.87	−2.20	+2.04
50	85.88	2.86		
		Butyl *p*-Hydroxybenzoate		
70	74.35	2.94		
60	85.71	2.95	−1.99	+2.78
50	89.07	2.88		

[a] S, solubility coefficient. [b] $-\Delta\mu^{\circ}$, standard affinity (Kcal./mole). [c] ΔH°, standard heat of sorption (Kcal./mole). [d] ΔS°, standard entropy of sorption (cal./mole °).

the weak organic acids and methyl *p*-hydroxybenzoate. Based upon changes in entropy, as the solute migrates from one phase to another, there would be a greater probability of combination between the higher molecular weight esters and the polyamide than with the weak organic acids and the same substrate. This viewpoint seems to be well taken, in that the propyl and butyl esters show greater solubility coefficients and higher standard affinities for the polyamide.

The second method of interpreting entropy calculations is to relate them to the degree of randomness and disorder of a given system. Classically, it is well accepted that the more natural system will have a completely randomized distribution of components within the system. As randomness and disorder increases, a corresponding increase in the entropy of the system is also seen. Thus, the system with the higher entropy value will be the one in which the greater degree of random distribution is present. Therefore, should entropy calculations for a particular drug–plastic interaction indicate an increase in entropy, then the solute is traveling into a more random distribution. Conversely, should calculations result in a decrease in the entropy of the system, then the solute is being firmly bound at fixed specific sites in the plastic.

Table III shows that a decrease in entropy occurs for the binding of the weak organic acids and methyl *p*-hydroxybenzoate by the polyamide. When one considers both the entropy change and the standard heats of sorption for these compounds sorbed by the polyamide, the assumption of hydrogen-bond formation at the amide linkages of the polymer appears rational. Reduction of the entropy of these systems indicates that the solutes are being held in fixed, specific sites in the plastic. The higher entropy of sorption values for propyl and butyl *p*-hydroxybenzoate indicate that these compounds are being more randomly distributed throughout the polymer, *via* the formation of weak secondary valence forces at various nonspecific sites along the polymer chain. It is felt that the phenolic hydroxyl group present in these two compounds serves as a primary attractive force, bringing the molecules into the proximity of the amide linkages. However, as the size of the ester moiety is increased, the solute is pulled away from these amide linkages, and becomes more randomly distributed throughout the chains.

Permeation and Diffusion Studies.—The data presented in Table IV, listing the permeability constants and apparent diffusion coefficients for these compounds in the polyamide, allow certain relationships to be drawn.

It is noted that in general the rate of permeation is directly dependent upon the quantity of solute originally present in the high-concentration side of the cell. Thus, as the initial concentration of a given solute is lowered, there will be a decrease in the permeation rate for that compound through the polyamide. Since permeation follows a steady state relationship, the concentration of solute within the film remains constant, and as much solute escapes from one side of the film as enters the other side. As the amount of solute entering the film is increased, more solute appears in the low concentration side per unit time, and the rate of permeation increases.

Where the permeation process is concerned with the rate of escape of solute molecules from the film into another phase, the actual travel of these molecules through the matrix of the plastic is considered to be the diffusion process. The time between initial contact at the one side and the final escape from the opposite side is the time during which the diffusion process occurs.

It is also noted that the original concentration of solute will affect the diffusion rate, but in a different manner than with permeation. Diffusion concerns itself only with the amount of solute within the matrix of the film, and not with the concentration surrounding it. Thus, diffusion is a function of the number of solute molecules capable of entering the polymer matrix, which may not be dependent upon the external environment.

Table IV shows that as the initial concentration of benzoic and *p*-hydroxybenzoic acids is increased, the diffusion rate is lowered. Due to the probability of greater degrees of dimerization in higher concentrations, through random movement and collision of molecules in solution, there would result the formation of complexes too large and bulky to enter the polymer matrix. As concentration is reduced, more individual molecules are available to diffuse into the film, and the diffusion rate increases. This effect has also been noted by Barrer and Barrie in the diffusion of water through ethyl cellulose (8). Vasenin (9) reported on the formation of clusters with increased concentrations of various paraffins and olefins in studies on their diffusion through certain polymers, while Peters (10) encountered similar phenomena with the diffusion of dye molecules through polymer films and fibers.

This effect is not noted with salicylic acid, probably due to the formation of intramolecular hydrogen bonds between the *ortho*-hydroxyl group and the carboxyl group, thus reducing the possibility of dimer formation. Since the esters have no carboxyl groups, dimerization is eliminated, and diffusion rates increase directly with increased original concentrations.

As the size of the solute is increased in a homologous series, (as with the esters of *p*-hydroxybenzoic acid), a decrease in the rates of permeation and diffusion is noted.

Activation Energies of Diffusion and Permeation.—Activation energy refers to the amount of energy a given molecule must acquire in order for it to be capable of overcoming the restraint of its surroundings. This energy is obtained through random exchange with neighboring molecules, and is temperature dependent in that molecular movement is directly related to increased temperature.

Table V presents the activation energies of diffusion and permeation for the compounds studied in this investigation. As in the cases of permeation and diffusion, increases in the molecular weight of a homologous series of compounds will affect the activation energy for the process. Thus, more energy is needed for the movement of the bulkier and heavier butyl *p*-hydroxybenzoate than for methyl *p*-hydroxybenzoate.

Kinetic Studies Versus Equilibrium Sorption Studies.—Table VI lists the thermodynamic constants calculated from permeation and diffusion studies, and shows the close agreement with similar constants derived from equilibrium sorption studies for each compound studied (Tables II and III).

Since sorption studies require a time period of approximately 14 days to complete, and permeation studies may be completed in less than 48 hr., it is apparent that the latter method is of extreme value. Permeation and diffusion studies reveal data of a kinetic nature as well as valid approximations of thermodynamic constants leading to possible suggested mechanisms of interaction.

SUMMARY

Studies were conducted on the interaction of six weak organic acids and phenols with a polyamide, at a number of concentrations and three temperatures. From these experiments, it was possible to evaluate several constants for each individual interaction, such as (*a*) the solubility coefficient of the solute in the polyamide, (*b*) the standard affinity, (*c*) the standard heat of sorption, (*d*) the standard entropy of sorption, (*e*) the apparent diffusion coefficient, (*f*) the permeability constant, and (*g*) the activation energies of permeation and diffusion.

Values obtained for the standard heats of sorption and standard entropies of sorption for the interaction of the polyamide with benzoic, salicylic, and *p*-hydroxybenzoic acids and methyl *p*-hydroxybenzoate, indicate the formation of hydrogen bonds between these compounds and the polyamide at the amide linkages of the nylon chains. Constants calculated for the propyl and butyl esters of *p*-hydroxybenzoic acid show that these compounds are bound to the polyamide through weak secondary valence forces, and are randomly distributed throughout the polymer chains.

Apparent diffusion coefficients for the diffusion of benzoic acid and *p*-hydroxybenzoic acid in the polyamide reveal that increased initial concentrations lead to lower apparent diffusion coefficients, due to the formation of dimers incapable of entering the polymer matrix.

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