KINETIC STUDY OF HYDROLYSIS OF BENZOATES. PART XXV. *Ortho* SUBSTITUENT EFFECT IN ALKALINE HYDROLYSIS OF PHENYL ESTERS OF SUBSTITUTED BENZOIC ACIDS IN WATER

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The second-order rate constants k_2 for alkaline hydrolysis of phenyl esters of *meta*-, *para*- and *ortho*-substituted benzoic acids, X-$C_6H_4CO_2C_6H_5$ (X = H, 3-Cl, 3-NO_2, 3-CH_3, 4-NO_2, 4-Cl, 4-F, 4-CH_3, 4-OCH_3, 4-NH_2, 2-NO_2, 2-CN, 2-F, 2-Cl, 2-Br, 2-I, 2-CH_3, 2-OCH_3, 2-CF_3, 2-NH_2), and of substituted phenyl esters of benzoic acid, $C_6H_5CO_2C_6H_4$-X (X = 2-I, 2-CF_3, 2-$C(CH_3)_3$, 4-Cl, 4-CH_3, 4-OCH_3, 4-NH_2), have been measured spectrophotometrically in water at 25 °C. The substituent effect in alkaline hydrolysis of phenyl esters of *para*-substituted benzoic acids, similar to that for ethyl esters of *para*-substituted benzoic acids, was found to be precisely described by the Hammett relationship ($\rho = 1.7$ in water). The log k value for alkaline hydrolysis of phenyl and ethyl esters of *meta*-, *para*- and *ortho*-substituted benzoic acids, X-$C_6H_4CO_2R$, was nicely correlated with $\log k_{\mathrm{m,p,ortho}} = \log k_{\mathrm{o}} + (\rho)_{\mathrm{m,p}}\sigma + (\rho_{\mathrm{I}})_{\mathrm{ortho}}\sigma_{\mathrm{I}} + (\rho^{\circ}_{\mathrm{R}})_{\mathrm{ortho}}\sigma^{\circ}_{\mathrm{R}} + \delta_{\mathrm{ortho}}E_{\mathrm{s}}^{\mathrm{B}}$ where σ, σ_{I}, $\sigma^{\circ}_{\mathrm{R}}$ are the Hammett polar, Taft inductive and Taft resonance ($\sigma^{\circ}_{\mathrm{R}} = \sigma^{\circ} - \sigma_{\mathrm{I}}$) substituent constants, respectively. $E_{\mathrm{s}}^{\mathrm{B}}$ is the steric scale for *ortho* substituents calculated on the basis of the log k values for the acid hydrolysis of *ortho*-substituted phenyl benzoates in water owing to the *ortho* substituent in the phenyl of phenyl benzoates. In water, the main factors responsible for changes in the *ortho* substituent effect in alkaline hydrolysis of phenyl and ethyl esters of *ortho*-substituted benzoic acids, X-$C_6H_4CO_2R$, were found to be the inductive and steric factors while the role of the resonance term was negligible ($(\rho^{\circ}_{\mathrm{R}})_{\mathrm{ortho}}$ ca. 0.3). In alkaline hydrolysis of substituted benzoates in neat water, the *ortho* inductive effect appeared to be 1.5 times and steric influence 2.7 times higher than the corresponding influences from the *ortho* position in the phenyl of phenyl benzoates. The contributions of the steric effects in alkaline hydrolysis of esters of *ortho*-substituted benzoic acids was found to be approximately the same as in acid hydrolysis of esters of *ortho*-substituted benzoic and acid esterification of *ortho*-substituted benzoic acids.

Keywords: Esters; Phenyl benzoates; Alkaline hydrolysis; *Ortho* effect; Substituent effects; Hammett equation.

In our previous papers the influence of the substituent effects, in particular *ortho* substituents, on the kinetics of alkaline hydrolysis of *meta*-, *para*- and

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ortho-substituted phenyl esters of benzoic acid, $C_6H_5CO_2C_6H_4X$, in water, aqueous 80% DMSO, 2.25 M Bu_4NBr, 1.0 M Bu_4NBr, 0.5 M Bu_4NBr, 5.3 M $NaClO_4$ and 4.8 M NaCl (see lit.[1–5] and references therein) has been studied. In the present paper we extended the study of the *ortho* substituent effects to the acyl part of substituted phenyl benzoates. With that aim in the present work the second-order rate constants for alkaline hydrolysis of phenyl esters of substituted benzoic acid, $X\text{-}C_6H_4CO_2C_6H_5$ (X = H, 3-Cl, 3-NO_2, 3-CH_3, 4-NO_2, 4-Cl, 4-F, 4-CH_3, 4-OCH_3, 4-NH_2, 2-NO_2, 2-CN, 2-F, 2-Cl, 2-Br, 2-I, 2-CH_3, 2-OCH_3, 2-CF_3, 2-NH_2), in neat water at 25 °C were determined and analyzed. Recently, Bauerová and Ludwig[6,7] studied the substituent effects in the base-catalyzed hydrolysis of phenyl esters of *para*- and *ortho*-substituted benzoic acid, $X\text{-}C_6H_4CO_2C_6H_5$, in 50% (v/v) aqueous dimethyl sulfoxide at 25 °C. To our knowledge, no systematic kinetic data on alkaline hydrolysis in water of phenyl esters of substituted benzoic acids containing *ortho*-substituted derivatives together with *meta*- and *para*-substituted derivatives are in literature.

The main purpose of the present work was to check which structure factors, inductive, resonance, or steric, are responsible for the *ortho* substituent effect in alkaline hydrolysis of phenyl esters of substituted benzoic acids in water and to compare the susceptibilities to the corresponding structure factors in acyl and in aryl part of phenyl benzoates. To separate the inductive, resonance and steric components, the kinetic data for alkaline hydrolysis of phenyl esters of substituted benzoic acids were subjected to correlation analysis using the Charton and the combined Hammett–Charton equations.

Compared to alkaline hydrolysis of phenyl esters of substituted benzoic acids, much more kinetic data are available in literature for alkaline hydrolysis of ethyl esters of substituted benzoic acids, $X\text{-}C_6H_4CO_2C_2H_5$, in various media[8–13] including the data for *ortho*-, *meta*- and *para*-substituted derivatives in the same reaction series. To compare the substituent effects, in particular the *ortho* effects in alkaline hydrolysis of phenyl esters of substituted benzoic acids with the substituent effects in alkaline hydrolysis of ethyl esters of substituted benzoic acids, the kinetic data for substituted ethyl benzoates in 5% aqueous ethanol, 56% (w/w) aqueous acetone, 85% (w/w) aqueous ethanol and 65% aqueous DMSO were treated using the Hammett, Charton and the combined Hammett–Charton equations.

It was interesting to compare the contribution of the steric effects of *ortho* substituents in alkaline hydrolysis of phenyl and ethyl esters of *ortho*-substituted benzoic acids with those in acid hydrolysis of esters used to calculate the polar substituent constants σ^*_o (ref.[14]) for *ortho* substituents from the Ingold–Taft equation. Therefore the rate data for acid-catalyzed esterification of both *ortho*-substituted and *meta*- or *para*-substituted benzoic acids with methanol and cyclohexanol and acid hydrolysis of *ortho*-substituted methyl benzoates taken from literature[8,15], were subjected to statistical analysis using the inductive σ_I, resonance σ°_R and steric $E_s{}^B$ scales.

Earlier (see lit.[1–5] and references therein) the log k values for alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4$-X, in the case of *meta* and *para* substituents were found to correlate with σ° constants. In the case of *ortho* substituents, the log k values for alkaline hydrolysis of substituted phenyl benzoates gave exellent correlation according the Charton equation using the inductive σ_I, the resonance σ°_R and steric $E_s{}^B$ scales ($E_s{}^B = \log k^{X}_{H^+} - \log k^{H}_{H^+}$, where $k^{X}_{H^+}$ and $k^{H}_{H^+}$ are the rate constants for acid hydrolysis of *ortho*-substituted and unsubstituted phenyl benzoates in water at 50 °C [2,5]). In water in alkaline hydrolysis of substituted phenyl benzoates, the inductive influence from *ortho* position was found to be 1.5 times stronger than that from *meta* and *para* position. In alkaline hydrolysis of substituted phenyl benzoates, the influence of the resonance term from *ortho* position appeared to be nearly the same as from *para* position. The variation of the inductive effect of *ortho* substituents with solvent was found to be ca. three times smaller than that for *para* substituents, while the *ortho* resonance term changed with solvent nearly similarly to that for *para* substituents. In alkaline hydrolysis of substituted phenyl benzoates, the susceptibility to the steric effect of *ortho* substituents δ ranged between 0.9 and 1.4 and the values of δ appeared approximately independent of the solvent character.

EXPERIMENTAL

Phenyl esters of substituted benzoic acids, X-$C_6H_4COOC_6H_5$ (X = 4-NO_2, 3-NO_2, 3-Cl, 4-Cl, 4-F, 4-OCH_3, 4-CH_3, 3-CH_3, 2-CF_3), were synthesized by the Schotten–Baumann method from the corresponding substituted benzoyl chlorides by the reaction with phenol in 10% aqueous NaOH solution and then recrystallized from aqueous ethanol. Purity of esters was determined by comparing their melting points with those reported in the literature. Phenyl 4-nitrobenzoate: yield 65%, m.p. 126 °C (ref.[6] 119–121 °C, ref.[16] 128–129 °C, ref.[17] 126 °C). Phenyl 3-nitrobenzoate: yield 54%, m.p. 95.4–96.0 °C (ref.[17] 98 °C, ref.[18] 90–92 °C). Phenyl 3-chlorobenzoate: yield 46%, m.p. 55.5–55.9 °C (ref.[17] 53 °C, ref.[18] 57–58 °C). Phenyl 4-chlorobenzoate: yield 72%, m.p. 101.7–102.2 °C (ref.[16] 103.5–104.5 °C, ref.[17] 100 °C, ref.[19] 100.5–101.5 °C). Phenyl 4-fluorobenzoate: yield 61%, m.p. 61.8 °C (ref.[6] 51–53 °C, ref.[20] 63.5–64.5 °C). Phenyl 4-methylbenzoate: yield 78%, m.p. 72.8–73.7 °C (ref.[17] 73 °C, ref.[19] 70.5–72.5 °C). Phenyl 4-methoxybenzoate: yield 72%, m.p. 71.1–71.8 °C (ref.[19] 67.5–69 °C).

Phenyl 3-methylbenzoate: yield 30%, b.p. 129–130 °C/186 Pa (m.p. ref.[17] 59 °C). Phenyl 2-(trifluoromethyl)benzoate: 41%, b.p. 125–126 °C /106 Pa (ref.[7] 106–108 °C/133 Pa).

Phenyl 4-aminobenzoate was synthesized from 4-nitrobenzoate in anhydrous ethanol by reduction with $SnCl_2 \cdot 2H_2O$ in concentrated HCl solution: yield 12%, m.p. 167.5–168.3 °C (ref.[21] 173 °C).

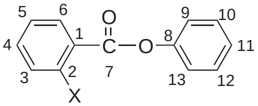
Phenyl esters of substituted benzoic acids, $X\text{-}C_6H_4CO_2C_6H_5$ (X = 2-F, 2-Cl, 2-OCH_3, 2-CH_3), were synthesized from the corresponding substituted benzoyl chlorides and phenol in pyridine solution (the Einhorn method[22]). Phenyl 2-fluorobenzoate: yield 89%, m.p. 69.0–70.0 °C (ref.[23] 70–71 °C). Phenyl 2-chlorobenzoate: yield 59%, b.p. 144–145 °C/133 Pa (ref.[24] 138 °C/80 Pa). Phenyl 2-methoxybenzoate: yield 77%, m.p. 56.2–57.2 °C (ref.[25] 57–58 °C). Phenyl 2-methylbenzoate: yield 47%, b.p. 125–127 °C/93 Pa.

Phenyl benzoates, $X\text{-}C_6H_4COOC_6H_5$ (X = 2-NO_2, 2-Br, 2-OCH_3, 2-I), were synthesized by addition of one equivalent of $SOCl_2$ to an equimolar mixture of the corresponding substituted benzoic acid and phenol in pyridine[8]. Phenyl 2-nitrobenzoate: yield 69%, m.p. 50.5–52.4 °C (ref.[18] 50–52 °C, ref.[23] 52–53 °C). Phenyl 2-bromobenzoate: yield 17%, b.p. 142–143 °C/80 Pa (ref.[7] 137–139 °C/133 Pa). Phenyl 2-iodobenzoate: yield 16%, b.p. 165–167 °C/93 Pa (ref.[7,26] 146–148 °C/133 Pa).

Phenyl 2-cyanobenzoate was synthesized similarly to ethyl 2-cyanobenzoate[27] from phthalic monoamide and phenol in pyridine solution in the presence of *p*-toluenesulfonyl chloride: yield 68%, m.p. 70–71 °C (ref.[28] 73 °C).

Phenyl 2-aminobenzoate was obtained from isatoic acid anhydride and phenol in 1,4-dioxane solution in the presence of NaOH pellets[29]: yield 87%, m.p. 69.4–70.1 °C (ref.[30] 70 °C).

Purity of substituted phenyl benzoates, $X\text{-}C_6H_4COOC_6H_5$ (X = 2-Cl, 2-Br, 2-I, 2-CH_3, 2-CF_3), was confirmed by ^1H and ^{13}C NMR spectroscopy. The ^1H and ^{13}C NMR spectra were measured in deuterated chloroform. The ^1H and ^{13}C NMR chemical shifts δ (in ppm) were measured at 25 °C with the Bruker AC-200 spectrometer operating at 200.13 MHz for ^1H and at 50.32 MHz for ^{13}C. The chemical shifts are referenced to an internal TMS. Coupling constants (*J*) are given in Hz.

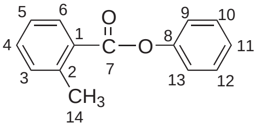


Phenyl 2-chlorobenzoate (X = Cl): ^1H NMR: 7.20–7.55 m, 8 H (H-3,4,5,9,10,11,12,13); 8.03 m, 1 H (H-6), ^3J = 7.7. ^{13}C NMR: 129.60 (C-1); 134.36 (C-2); 131.31 (C-3); 133.08 (C-4); 126.73 (C-5); 131.82 (C-6); 164.05 (C-7); 150.83 (C-8); 121.61 (C-9,13); 129.52 (C-10,12); 126.08 (C-11).

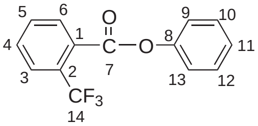
Phenyl 2-bromobenzoate (X = Br): ^1H NMR: 7.72 m, 1 H (H-3); 7.20–7.50 m, 7 H (H-4,5,9,10,11,12,13); 8.00 m, 1 H (H-6). ^{13}C NMR: 131.71 (C-1); 122.22 (C-2); 133.04 (C-3); 134.61 (C-4); 127.30 (C-5); 131.74 (C-6); 164.54 (C-7); 150.84 (C-8); 121.58 (C-9,13); 129.52 (C-10,12); 126.10 (C-11).

Phenyl 2-iodobenzoate (X = I): ^1H NMR: 8.01 dd, 1 H (H-3), ^3J = 7.9, ^4J = 0.4; 7.15–7.24 m, 4 H (H-4,9,11,13); 7.35–7.45 m, 3 H (H-5,10,12); 8.00 dd, 1 H (H-6), ^3J = 7.8, ^4J = 0.4. ^{13}C NMR: 134.39 (C-1); 94.43 (C-2); 141.51 (C-3); 133.05 (C-4); 128.00 (C-5); 131.34 (C-6); 164.74 (C-7); 150.72 (C-8); 121.50 (C-9,13); 129.43 (C-10,12); 126.09 (C-11).

Phenyl 2-methylbenzoate (X = CH_3): ^{1}H NMR: 7.13–7.50 m, 8 H (H-3,4,5,9,10,11,12,13); 8.15 dd, 1 H (H-6), ^3J = 8.6, ^4J = 2.0; 2.66 s, 3 H (H-14). ^{13}C NMR: 128.79 (C-1); 141.17 (C-2); 131.12 (C-3); 132.62 (C-4); 125.90 (C-5); 131.93 (C-6); 165.76 (C-7); 151.07 (C-7); 121.82 (C-8,13); 129.44 (C-9,12); 125.75 (C-10); 21.82 (C-14).



Phenyl 2-(trifluoromethyl)benzoate: ^{1}H NMR: 7.75 m, 1 H (H-3); 7.50–7.65 m, 2 H (4,5); 7.92 m, 1 H (H-6); 7.15–7.30 m, 3 H (H-9,11,13); 7.30–7.45 m, 2 H (H-10,12). ^{13}C NMR: 129.04 q (C-2), $^2J_{C\text{-}F}$ = 32.6; 126.93 q (C-3), $^3J_{C\text{-}F}$ =5.4; 132.02 q (C-4), $^4J_{C\text{-}F}$ = 1.2; 131.77 (C-5); 130.61 (C-6); 165.23 (C-7); 150.89 (C-8); 121.44 (C-9,13); 129.66 (C-10,12); 126.32 (C-11); 123.69 q (C-14), $^1J_{C\text{-}F}$ = 273.6.



The preparation procedure and characteristics of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4$-X (X = 4-Cl, 4-CH_3, 4-OCH_3, 4-NH_2, 2-CF_3, 2-I, 2-$C(CH_3)_3$), were described in lit.[5]

The kinetics was measured spectrophotometrically as described earlier[1–4]. The kinetic measurements were carried out under pseudo-monomolecular conditions. The pseudo-first-order rate constants, k_1 (s^{-1}), were determined using a least-squares computer program. Rate constants for each phenyl esters of substituted benzoic acids were measured at various NaOH concentrations. The measurement at each hydroxide concentrations was repeated and the arithmetic means of the corresponding pseudo-first-order rate constants, k_1 (s^{-1}), were calculated. The second-order rate constants k ($dm^3\ mol^{-1}\ s^{-1}$) were calculated as slopes of the pseudo-first-order rate constants vs NaOH concentration dependences according to the following equation

$$k_1 = kc_{OH^-} + \text{const}\ . \qquad (1)$$

The second-order rate constants k for alkaline hydrolysis of phenyl esters of substituted benzoic acids, X-$C_6H_4CO_2C_6H_5$, in water at 25 °C and the wavelength λ used in spectrophotometric kinetic measurements are given in Table I.

The second-order rate constants k for alkaline hydrolysis of substituted phenyl esters of benzoic acids, $C_6H_5CO_2C_6H_4$-X (X = 4-Cl, 4-CH_3, 4-OCH_3, 4-NH_2, 2-CF_3, 2-I, 2-$C(CH_3)_3$), in water at 25 °C and the wavelength λ used in spectrophotometric kinetic measurements are given in Table II.

TABLE I
The second-order rate constants k (in $dm^3\ mol^{-1}\ s^{-1}$) for alkaline hydrolysis of phenyl esters of substituted benzoic acids, $X\text{-}C_6H_4CO_2C_6H_5$, in water at 25 °C

X	λ, nm[a]	k $dm^3\ mol^{-1}\ s^{-1}$[b]	n/n_1[c]	X	λ, nm[a]	k $dm^3\ mol^{-1}\ s^{-1}$[b]	n/n_1[c]
H	244, 292	0.363±0.008	8/34	$2\text{-}NO_2$	235, 292	1.25±0.04	4/414
3-Cl	225, 292	1.50±0.03	8/39	2-CN	235	8.47±0.44	4/14
$3\text{-}NO_2$	225, 292	5.59±0.17	5/24	2-F	230, 292	1.42±0.02	4/17
$3\text{-}CH_3$	250	0.296±0.009	3/8	2-Cl	250, 292	0.962±0.039	4/22
$4\text{-}NO_2$	235	7.90±0.54	5/20	2-Br	250, 292	0.657±0.031	4/25
4-Cl	282	0.837±0.028	5/22	2-I	250	0.530±0.035	4/12
4-F	245	0.470±0.006	3/14	$2\text{-}CF_3$	230	0.0780±0.0034	4/14
$4\text{-}CH_3$	235, 292	0.203±0.011	3/17	$2\text{-}NH_2$	235, 292	0.0416±0.0010	3/15
$4\text{-}OCH_3$	235	0.109±0.002	3/12	$2\text{-}OCH_3$	235	0.188±0.004	3/12
$4\text{-}NH_2$	235	0.0245±0.0015	3/9	$2\text{-}CH_3$	250, 292	0.0812±0.0027	3/15

[a] λ is the wavelength used in kinetic measurements. [b] To calculate the second-order rate constants, k, Eq. (*1*), $k_1 = kc_{OH^-}$ + const, was used. [c] n equals to the number of NaOH concentrations used to determine the k value according to Eq. (*1*), n_1 equals to the total number of measurements used in determination of the k value.

TABLE II
The second-order rate constants k (in $dm^3\ mol^{-1}\ s^{-1}$) for alkaline hydrolysis of substituted phenyl esters of benzoic acids, $C_6H_5CO_2C_6H_4\text{-}X$, in water at 25 °C

X	λ, nm[a]	k $dm^3\ mol^{-1}\ s^{-1}$[b]	n[c]	X	λ, nm[a]	k $dm^3\ mol^{-1}\ s^{-1}$[b]	n[c]
4-Cl	302	0.958±0.031	3	$2\text{-}CF_3$	301	0.703±0.026	4
$4\text{-}CH_3$	296	0.235±0.006	4	2-I	301	0.536±0.031	4
$4\text{-}OCH_3$	307	0.315±0.012	5	$2\text{-}C(CH_3)_3$	240	0.0745±0.0167	3
$4\text{-}NH_2$	240	0.192±0.007	3				

[a] λ is the wavelength used in kinetic measurements. [b] The second-order rate constants, k, were calculated by dividing the pseudo-first-order rate constants, k_1, by alkali concentration. 0.0192 M NaOH was used. [c] n equals to the number of measurements used to determine the value of k.

DATA PROCESSING

For study of the substituent effects in alkaline hydrolysis of phenyl esters of substituted benzoic acids, the log k values, measured in the present work (Table I) were treated using the Hammett[31] equation (*2*), the combined Hammett–Charton equation (*3*), and the Charton[32] equation (*4*)

$$\log k_{\mathrm{m,p}} = \log k_{\mathrm{o}} + (\rho)_{\mathrm{m,p}}\sigma \tag{2}$$

$$\log k_{\mathrm{m,p,ortho}} = \log k_{\mathrm{o}} + (\rho)_{\mathrm{m,p}}\,\sigma + (\rho_{\mathrm{I}})_{\mathrm{ortho}}\,\sigma_{\mathrm{I}} + (\rho^{\circ}_{\mathrm{R}})_{\mathrm{ortho}}\,\sigma^{\circ}_{\mathrm{R}} + \delta_{\mathrm{ortho}}\,E_{\mathrm{s}}^{\mathrm{B}} \tag{3}$$

$$\log k_{\mathrm{ortho}} = \log k_{\mathrm{o}} + (\rho_{\mathrm{I}})_{\mathrm{ortho}}\,\sigma_{\mathrm{I}} + (\rho^{\circ}_{\mathrm{R}})_{\mathrm{ortho}}\,\sigma^{\circ}_{\mathrm{R}} + \delta_{\mathrm{ortho}}\,E_{\mathrm{s}}^{\mathrm{B}}\ . \tag{4}$$

To correlate the log k values for *meta*- and *para*-substituted derivatives the Hammett equation (*2*) was used. The log k values for *ortho*-substituted derivatives together with *meta*- and *para*-substituted derivatives were treated using the Hammett–Charton combined equation (*3*). For comparison, the data only for *ortho*-substituted derivatives were correlatated with the Charton equation (*4*).

In the data processing, using the Eq. (*4*) the log k value for unsubstituted derivative (X = H) as standard was included besides the *ortho*-substituted derivatives. The values of the Hammett polar substituent constants, σ, reviewed by Hansch, Leo and Taft[33], the Taft inductive σ_{I} [34] and resonance $\sigma^{\circ}_{\mathrm{R}}$ constants[35] ($\sigma^{\circ}_{\mathrm{R}} = \sigma^{\circ} - \sigma_{\mathrm{I}}$) were used in the data processing. As the steric constants for *ortho* substituents we employed the values of $E_{\mathrm{s}}^{\mathrm{B}}$ determined on the basis of the acid hydrolysis of *ortho*-substituted phenyl benzoates, $C_6H_5CO_2C_6H_4$-X, with *ortho* substituents in the phenyl part[2,5] ($E_{\mathrm{s}}^{\mathrm{B}} = \log k^{\mathrm{X}}_{\mathrm{H^+}} - \log k^{\mathrm{H}}_{\mathrm{H^+}}$, where $k^{\mathrm{X}}_{\mathrm{H^+}}$ and $k^{\mathrm{H}}_{\mathrm{H^+}}$ are the rate constants for the acid hydrolysis of *ortho*-substituted and unsubstituted phenyl benzoates in water at 50 °C [36]). The values of σ_{I}, $\sigma^{\circ}_{\mathrm{R}}$ and $E_{\mathrm{s}}^{\mathrm{B}}$ are listed in Table VII. In the data processing using Eqs (*2*)–(*4*), the second-order rate constants k of alkaline hydrolysis of phenyl esters of *ortho*-, *meta*- and *para*-substituted benzoic acids at 25 °C, listed in Table I, were used. For comparison, the log k for alkaline hydrolysis of phenyl esters of *ortho*- and *para*-substituted benzoic acids in 50% aqueous DMSO reported by Bauerova and Ludwig[6,7] and ethyl esters of *ortho*-, *meta*- and *para*-substituted benzoic acids for 5% aqueous ethanol, 56% (w/w) aqueous acetone, 85% (w/w) aqueous ethanol and 65% aqueous DMSO at 25 °C, taken from literature[8], were processed using Eqs (*2*)–(*4*) as well (Tables III and IV). To compare steric contributions of *ortho* substituents in alkaline hydrolysis and in acid hydrolysis of esters, the log k values

TABLE III
Correlation of the log *k* values for alkaline hydrolysis of phenyl esters of substituted benzoic acids, X-$C_6H_4CO_2C_6H_5$, at 25 °C with Eqs (*2*)–(*4*) in water and 50% aqueous DMSO[6,7]

Reaction constant	*Meta* and *para* substituents Eq. (*2*)	Weight	*Ortho*, *meta* and *para* substituents Eq. (*3*)	Weight	*Ortho* substituents Eq. (*4*)	Weight
			Water[a]			
log k_o	–0.451±0.011		–0.433±0.045		–0.333±0.078	
			–0.439±0.042[b]		–0.363±0.084[b]	
			–0.438±0.065[c]		–0.356±0.102[c]	
$\rho_{m,p}$	1.720±0.025	1.00	1.710±0.055	0.538		
			1.713±0.046[b]	0.570		
			1.713±0.080[c]	0.544		
$(\rho_I)_{ortho}$			2.244±0.084	0.223	2.128±0.122	0.538
			2.193±0.075[b]	0.271	2.117±0.119[b]	0.636
			2.230±0.124[c]	0.224	2.123±0.163[c]	0.538
$(\rho^\circ_R)_{ortho}$			0.236±0.102	0.015	0.312±0.134	0.039
			0.398±0.105[b]	0.034	0.433±0.140[b]	0.082
			0.380±0.147[c]	0.025	0.442±0.171[c]	0.056
δ_{ortho}			2.536±0.117	0.223	2.669±0.160	0.423
			2.263±0.142[b]	0.125	2.398±0.214[b]	0.280
			–1.168±0.081[c]	0.207	–1.262±0.102[c]	0.406
n/n_0	10/10		20/20		11/11	
			17/17[b]		8/8[b]	
			20/20[c]		10/11[c]	
R	0.999		0.995		0.992	
			0.997[b]		0.994[b]	
			0.989[c]		0.987[c]	
s	0.033		0.072		0.085	
			0.060[b]		0.079[b]	
			0.106[c]		0.113[c]	
s_0	0.044		0.101		0.126	
			0.080[b]		0.105[b]	
			0.148[c]		0.160[c]	
t	0.990		0.990		0.990	
			0.990[b]		0.990[b]	
			0.999[c]		0.990[c]	

TABLE III
(*Continued*)

Reaction constant	*Meta* and *para* substituents Eq. (*2*)	Weight	*Ortho, meta* and *para* substituents Eq. (*3*)	Weight	*Ortho* substituents Eq. (*4*)	Weight
			50% aqueous DMSO[d]			
log k_o	–0.018±0.028		–0.015±0.065		0.047±0.104	
			–0.017±0.061[e]		0.021±0.122[e]	
$\rho_{m,p}$	2.322±0.062	1.00	2.321±0.061	0.836		
			2.322±0.061[e]	0.848		
$(\rho_I)_{ortho}$			2.357±0.157	0.062	2.310±0.157	0.62
			2.308±0.163[e]	0.079	2.284±0.164[e]	0.69
$(\rho°_R)_{ortho}$			0.726±0.160	0.021	0.777±0.167	0.102
			0.842±0.194[e]	0.027	0.862±0.189[e]	0.152
δ_{ortho}			2.593±0.197	0.081	2.693±0.232	0.276
			2.395±0.271[e]	0.045	2.477±0.323[e]	0.158
n/n_0	17/17		26/26		10/10	
			25/25[e]		9/9[e]	
R	0.994		0.993		0.987	
			0.993[e]		0.986[e]	
s	0.114		0.113		0.106	
			0.113[e]		0.106[e]	
s_0	0.105		0.119		0.167	
			0.117[e]		0.164[e]	
t	0.990		0.990		0.990	
			0.990[e]		0.990[e]	

[a] The log k values for *ortho*-substituted esters, X-$C_6H_4CO_2C_6H_5$, where X = H, 2-NO_2, 2-F, 2-I, 2-Br, 2-Cl, 2-NH_2, 2-CN, 2-OCH_3, 2-CF_3, 2-CH_3, were included. [b] The log k values for 2-CF_3, 2-I, 2-Br derivatives were excluded before data treatment. [c] In the case of *ortho*-substituted esters the steric scale of υ was used (Table VII). [d] The log k values for *ortho*-substituted esters where X = H, 2-NO_2, 2-F, 2-I, 2-Br, 2-Cl, 2-NH_2, 2-OCH_3, 2-CF_3, 2-CH_3, were included. [e] The log k value for 2-CF_3 derivative was excluded before data treatment.

TABLE IV
Correlation of the log *k* values for alkaline hydrolysis of ethyl esters of substituted benzoic acids, X-$C_6H_4CO_2C_2H_5$, with Eqs (*2*)–(*4*) at 25 °C for water, 56% aqueous acetone, 85% aqueous ethanol and 65% aqueous DMSO [8]

Reaction constant	*Meta* and *para* substituents Eq. (*2*)	Weight	*Ortho, meta* and *para* substituents Eq. (*3*)	Weight	*Ortho* substituents Eq. (*4*)	Weight
5% aqueous ethanol[a]						
log k_o	–1.483±0.031		–1.465±0.104		–1.444±0.241	
			–1.477±0.074[b]		–1.519±0.032[b]	
$\rho_{m,p}$	1.437±0.075	1.00	1.413±0.140	0.503		
			1.425±0.072[b]			
$(\rho_I)_{ortho}$			1.947±0.249	–0.043	1.942±0.359	0.546
			1.537±0.169[b]		1.532±0.429[b]	0.862
$(\rho^\circ_R)_{ortho}$			–		–	
			0.334±0.231[b]		0.293±0.061[b]	0.028
δ_{ortho}			3.466±0.339	0.540	3.526±0.689	0.454
			2.733±0.286[b]		2.595±0.094[b]	0.110
n/n_0	8/8		14/14		7/7	
			12/12[b]		5/5[b]	
R	0.991		0.975		0.930	
			0.991[b]		0.998[b]	
s	0.079		0.148		0.212	
			0.077[b]		0.019[b]	
s_0	0.136		0.221		0.368	
			0.138[b]		0.054[b]	
t	0.990		0.990		0.990	
			0.999[b]		0.990[b]	
56% (w/w) aqueous acetone[c]						
log k_o	–2.471±0.035		–2.472±0.096		–2.514±0.232	
			–2.472±0.084[d]		–2.521±0.202[d]	
$\rho_{m,p}$	2.332±0.079	1.00	2.333±0.093	0.766		
			2.333±0.084[d]	0.764		
$(\rho_I)_{ortho}$			2.357±0.157	0.046	2.394±0.325	
			2.457±0.188[d]	0.074	2.508±0.283[d]	
$(\rho^\circ_R)_{ortho}$			0.751±0.288	0.043	0.731±0.395	
			0.743±0.256[d]	0.041	0.720±0.340[d]	
δ_{ortho}			2.891±0.378	0.144	2.815±0.597	
			2.770±0.352[d]	0.120	2.683±0.514[d]	
n/n_0	19/19		28/28		10/10	
			26/26[d]		8/8[d]	

TABLE IV
(*Continued*)

Reaction constant	*Meta* and *para* substituents Eq. (*2*)	Weight	*Ortho*, *meta* and *para* substituents Eq. (*3*)	Weight	*Ortho* substituents Eq. (*4*)	Weight
R	0.990		0.985 0.988^d		0.960 0.978^d	
s	0.141		0.167 0.152^d		0.225 0.190^d	
s_0	0.142		0.175 0.154^d		0.278 0.209^d	
t	0.990		0.990 0.999^d		0.999 0.999^d	
85% (w/w) aqueous ethanol[e]						
$\log k_o$	–3.168±0.044		–3.167±0.075		–3.207±0.062	
$\rho_{m,p}$	2.546±0.097	1.00	2.544±0.089	0.772		
$(\rho_I)_{ortho}$			2.607±0.142	0.062	2.608±0.080	
$(\rho^\circ_R)_{ortho}$	0.991		1.228±0.182	0.046	1.178±0.112	
δ_{ortho}			2.637±0.272	0.119	2.507±0.191	
n/n_0	6/6		10/10		5/5	
R	0.996		0.997		0.998	
s	0.081		0.074		0.042	
s_0	0.085		0.083		0.060	
t	0.990		0.990		0.990	
65% (w/w) aqueous DMSO[f]						
$\log k_o$	–1.397±0.027		–1.401±0.072		–1.476±0.101	
$\rho_{m,p}$	2.376±0.069	1.00	2.379±0.077	0.690		
$(\rho_I)_{ortho}$			2.257±0.150	0.151	2.249±0.146	
$(\rho^\circ_R)_{ortho}$			1.247±0.152	0.103	1.216±0.149	
δ_{ortho}			2.161±0.243	0.056	1.921±0.292	
n/n_0	5/5		9/9		5/5	
R	0.998		0.997		0.996	
s	0.058		0.064		0.062	
s_0	0.058		0.074		0.093	
t	0.990		0.990		0.990	

[a] The log *k* values for *ortho*-substituted esters, $X-C_6H_4CO_2C_2H_5$, where X = H, 2-NO_2, 2-Br, 2-Cl, 2-NH_2, 2-OCH_3, 2-CH_3, were included. [b] The log *k* values for 2-OCH_3 and 2-NH_2 derivatives were excluded before data treatment. [c] The log *k* values for *ortho*-substituted esters, when X = H, 2-NO_2, 2-CN, 2-F, 2-Br, 2-Cl, 2-I, 2-NH_2, 2-OCH_3, 2-CH_3, were included. [d] The log *k* values for 2-CF_3, 2-I, 2-Br derivatives were excluded before data treatment. [e] The log *k* values for *ortho*-substituted esters, when X = H, 2-NO_2, 2-F, 2-Cl, 2-CH_3, were included. [f] The log *k* values for *ortho*-substituted esters, when X = H, 2-NO_2, 2-Cl, 2-OCH_3, 2-CH_3, were included.

for acid esterification of substituted benzoic acids in methanol at 25 °C [15], acid hydrolysis of substituted methyl esters in 80% (v/v) aqueous methanol at 100.8 °C [8] and acid esterification of substituted benzoic acids in cyclohexanol at 55 °C [15] were correlated with Eq. (*3*) as well (Table V).

The results of the data treatment with Eqs (*2*)–(*4*) for alkaline hydrolysis of substituted phenyl benzoates in water at 25 °C including the rate constants measured in the present work and those reported earlier[1] are shown in Table VI.

For comparison, we correlated the log *k* values for alkaline hydrolysis of phenyl esters of *ortho*-, *meta*- and *para*-substituted benzoic acids at 25 °C, substituted phenyl benzoates in water at 25 °C and for acid esterification of

TABLE V

The results of correlation of the Taft steric E°_s values[14] with Eq. (*4*) and the log *k* values for acid esterification of substituted benzoic acids in methanol at 25 °C [15] (set A), acid hydrolysis of substituted methyl esters in 80% (v/v) aqueous methanol at 100.8 °C [8] (set B) and acid esterification of substituted benzoic acids in cyclohexanol at 55 °C[15] (set C) with Eq. (*3*)

Reaction constant	Taft steric E°_s [a] Eq. (*4*)	Set A[b] Eq. (*3*)	Set B[c] Eq. (*3*)	Set C[d] Eq. (*3*)
log k_o	0.518±0.176	–3.696±0.052 –3.713±0.067[e]	–3.787±0.084	–4.741±0.057
$\rho_{m,p}$		–0.525±0.063 –0.497±0.085[e]	–0.119±0.087	0.320±0.090
$(\rho_I)_{ortho}$	–0.135±0.119	–0.365±0.101 –0.491±0.101	–0.556±0.163	0.122±0.113
$(\rho^\circ_R)_{ortho}$	–1.262±0.284	–1.793±0.128 –1.885±0.167[e]	–1.641±0.328	–1.021±0.124
δ_{ortho}	2.520±0.466	2.657±0.182 –1.087±0.102[e]	3.076±0.201	1.852±0.196
n/n_0	7/7	14/14 14/14[e]	9/9	15/15
R	0.993	0.992 0.985[e]	0.986	0.981
s	0.062	0.053 0.071[e]	0.054	0.060
s_0	0.112	0.126 0.170[e]	0.168	0.193

[a] The Taft steric E°_s values for 2-NO_2, 2-Cl, 2-F, 2-Br, 2-I, 2-CH_3, 2-OCH_3 were included. [b] 2-NO_2, 2-Cl, 2-F, 2-Br, 2-I, 2-CH_3 derivatives were included. The log *k* value for 2-OCH_3 derivative was excluded. [c] 2-Cl, 2-F, 2-Br, 2-I, 2-CH_3 derivatives included. [d] 2-NO_2, 2-Cl, 2-F, 2-Br, 2-I, 2-CH_3, 2-OCH_3 derivatives included. [e] In the case of *ortho* substituted esters the steric scale of υ was used (Table VII).

TABLE VI
The results of the correlation of the log *k* values for alkaline hydrolysis of substituted phenyl esters of benzoic acids, $C_6H_5CO_2C_6H_4$-X, with Eqs (*2*)–(*4*) at 25 °C in water

Reaction constant	*Meta* and *para* substituents Eq. (*2*)	Weight	*Ortho*, *meta* and *para* substituents Eq. (*3*)	Weight	*Ortho* substituents Eq. (*4*)	Weight
			Water^{a}			
log k_o	−0.396±0.035		−0.396±0.045		−0.406±0.078	
			−0.399±0.033^{b}		−0.430±0.027^{b}	
			−0.397±0.034^{c}		−0.410±0.061^{c}	
$\rho_{m,p}$	1.145±0.046	1.00	1.142±0.051	0.404		
			1.145±0.041^{b}	0.705		
			1.143±0.050^{c}	0.405		
$(\rho_I)_{ortho}$			1.549±0.067	0.261	1.560±0.097	0.590
			1.566±0.041^{b}	0.136	1.573±0.041^{b}	0.941
			1.541±0.066^{c}	0.260	1.556±0.041^{c}	
$(\rho^{\circ}_R)_{ortho}$			1.077±0.085	0.190	1.070±0.104	0.267
			1.097±0.159^{b}	0.013	1.033±0.083^{b}	−0.092
			1.166±0.085^{b}	0.202	1.155±0.104^{c}	
δ_{ortho}			0.952±0.080	0.144	0.937±0.122	0.142
			−0.427±0.034^{b}	0.146	−0.400±0.023^{b}	0.152
			−0.449±0.038^{c}	0.133	−0.440±0.056^{c}	
n/n_0	12/12		22/22		11/11	
			18/18^{b}		7/7^{b}	
			22/22^{c}		11/11^{c}	
R	0.991		0.992		0.992	
			0.993^{b}		0.998^{b}	
			0.993^{c}		0.993^{c}	
s	0.059		0.065		0.075	
			0.052^{b}		0.024^{b}	
			0.064^{c}		0.073^{c}	
s_0	0.131		0.123		0.126	
			0.117^{b}		0.060^{b}	
			0.121^{c}		0.123^{c}	
t	0.990		0.990		0.990	
			0.990^{b}		0.990^{b}	
			0.990^{c}		0.993^{c}	

[a] The Taft substituent constants σ° used in Eqs (*2*) and (*3*). The log *k* values for *ortho*-substituted esters, $C_6H_4CO_2C_6H_4$-X, where X = H, 2-NO_2, 2-CN, 2-F, 2-I, 2-Cl, 2-$N(CH_3)_2$, 2-OCH_3, 2-CF_3, 2-CH_3 2-$C(CH_3)_3$, were included. [b] In the case of *ortho*-substituted esters the steric scale of υ was used (Table VII). X = H, 2-F, 2-I, 2-Cl, 2-CF_3, 2-CH_3, 2-$C(CH_3)_3$ derivatives were included. [c] The steric scale of υ was used. X = H, 2-NO_2, 2-CN, 2-F, 2-I, 2-Cl, 2-$N(CH_3)_2$, 2-OCH_3, 2-CF_3, 2-CH_3, 2-$C(CH_3)_3$ derivatives were included.

substituted benzoic acids in methanol at 25 °C [15] with Eqs (*3*) and (*4*) using two steric scales for *ortho* substituents: the E_s^B constants and the Charton scale of υ [37] (Tables III, V and VI).

In the case of substituents X = H, F, Br, Cl, I, CH_3, *t*-Bu, CF_3, the steric constants E_s^B appeared to be nearly linear function of the υ values, based on a consideration of van der Waals radii r_v. The values of r_v proposed in lit-

TABLE VII
Substituent parameters for correlations using Eqs (*3*) and (*4*)

X	σ_I [34]	σ_R° [34]	E_s^B [2,5,36]	υ [37,d]
H	0	0	0	0
2-NO_2	0.63	0.19	–0.374	0.76[e]
2-CN	0.58	0.11	–0.030	0[f]
2-F	0.52	–0.35	–0.155	0.27[37]
2-Cl	0.47	–0.20	–0.243	0.55[37]
2-Br	0.45	–0.19	–0.270[a]	0.65[37]
2-I	0.39	–0.12	–0.300[b]	0.78[37]
2-NH_2	0.10	–0.48	–0.425	0.76[e]
2-$N(CH_3)_2$	0.10	–0.54	–0.425	0.76[e]
2-CH_3	–0.05	–0.10	–0.264	0.56[37]
2-CF_3	0.41	0.10	–0.593[c]	1.24[g]
2-OCH_3	0.25	–0.41	–0.308	0.56[h]
2-$C(CH_3)_3$	–0.07	–0.08	–0.604	1.24[37]

[a] Average value, calculated from $\log k = 0.477 + (1.145)_{o,m,p}\sigma^\circ + (0.454)_o\sigma_I + 0.884E_s^B$ (R = 0.990, s = 0.06), where k are the rate constants for alkaline hydrolysis of substituted phenyl acetates in 3% ethanol at 25 °C; from $\log k = -4.364 + (1.108)_{o,m,p}\sigma^\circ + 1.660E_s^B$ (R = 0.987, s = 0.07), where k are the rate constants for alkaline hydrolysis of substituted phenyl *N,N*-dimethyl carbamates (Nishioka T, Fujita T., Kimutara K., Nakajima M.: *J. Org. Chem.* **1975**, *40*, 2520); and from kinetic data for alkaline hydrolysis of substituted ethyl benzoates in 5% aqueous ethanol[9] (Table IV in the present work). [b] Average value, calculated from $\log k = 0.477 + (1.145)_{o,m,p}\sigma^\circ + (0.454)_o\sigma_I + 0.884E_s^B$ (R = 0.990, s = 0.06), where k are the rate constants for alkaline hydrolysis of substituted phenyl acetates in 3% ethanol at 25 °C and kinetic data for alkaline hydrolysis of substituted phenyl benzoates in water at 25 °C [5] (Table VI in the present work). [c] Average value, calculated from kinetic data for alkaline hydrolysis of phenyl esters of substituted benzoic acids in 50% aqueous DMSO (Table III in the present work) and kinetic data for alkaline hydrolysis of substituted phenyl esters of benzoic acid in water (Table VI in the present work). [d] $\nu = r_{vX} - r_{vH}$. [e] The value of υ for iPr [37] was used. [f] The value of υ for H [37] was used. [g] The value of υ for *t*-Bu [37] was used. [h] The value of υ for Et [37] was used.

erature for the polyatomic substituents NO_2 (υ = 0.35 [37], 1.39 [37], 0.98 [38], 0.59 [39]), NH_2 (υ = 0.35 [37,40]), $N(CH_3)_2$ (υ = 0.43 [40]), OCH_3 (υ = 0.36 [40]) and CN (υ = 0.40 [37,40]) deviate from this linearity. Therefore, we used in correlations for polyatomic substituents the value of υ for the following isosterical substituents[41]: for NO_2, NH_2, $N(CH_3)_2$ the value of υ for $CH(CH_3)_2$ (υ = 0.76 [37]) and for OCH_3 the value of υ for CH_2CH_3 (υ = 0.56 [37]) (Table VII).

The data processing was carried out using a multiple parameter linear least-squares (LLSQ) procedure[42]. Significantly deviating points were excluded using the Student criterion. Results of the data treatment in the present work are given mainly on the confidence level $t = 0.99$.

DISCUSSION

Effect of Place of Substitution

Previously[6], the variation of the reaction rates due to the polar effect of substituents in alkaline hydrolysis of phenyl esters of *para*-substituted benzoic acids in 50% aqueous DMSO at 25 °C and in alkaline hydrolysis of ethyl esters of *para*-substituted benzoic acids in various media has been described by the Hammett σ constants[9,10,31]. Similarly, the log k values for alkaline hydrolysis of phenyl esters of *meta*- and *para*-substituted benzoic acids in water at 25 °C, determined in the present work, gave excellent correlation with the Hammett σ constants (Table III). The susceptibility to the polar effect of *meta* and *para* substituents in alkaline hydrolysis of phenyl esters of *meta*- and *para*-substituted benzoic acids in water at 25 °C ($\rho_{m,p}$ = 1.72) is comparable with the polar substituent effect in alkaline hydrolysis of ethyl esters of *meta*- and *para*-substituted benzoic acids in 5% aqueous ethanol at 25 °C ($\rho_{m,p}$ = 1.44) (Table IV). The susceptibility to the polar effect of *meta* and *para* substituents in alkaline hydrolysis of phenyl esters of *meta*- and *para*-substituted benzoic acids in water at 25 °C is 1.6 times higher than the polar effect in alkaline hydrolysis of *meta*- and *para*-substituted phenyl esters of benzoic acid in neat water at 25 °C ($\rho^\circ_{m,p}$ = 1.14) (Table VI). Consequently, in alkaline hydrolysis of substituted phenyl benzoates in water at 25 °C, the polar effect of *meta* and *para* substituents from acyl component appeared to be ca. 1.6 times higher than the polar influence of *meta* and *para* substituents from the phenyl component.

Previously[1–5], in alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4$-X, the influence of *ortho* substituents from the phenyl component of ester in various media and at various temperatures was precisely described by the inductive, σ_I, resonance, σ°_R, and steric, E_s^B, constants (Table VII). Therefore, in the present paper we used the same substituent constants for *ortho* substituents (σ_I, σ°_R, E_s^B) to correlate the log *k* values for alkaline hydrolysis of phenyl and ethyl esters of *ortho*-substituted benzoic acids ($X\text{-}C_6H_4CO_2C_6H_5$, $X\text{-}C_6H_4CO_2C_2H_5$), including *ortho* substituents in the acyl component of ester. The values of reaction constants $(\rho_I)_{ortho}$, $(\rho^\circ_R)_{ortho}$ and δ_{ortho} calculated from Eq. (*4*) separately for *ortho*-substituted derivatives are approximately the same as those calculated together with *ortho*-, *meta*- and *para*-substituted derivatives using Eq. (*3*) (see Tables III and IV).

The influence of the *ortho* substituents in alkaline hydrolysis of phenyl and ethyl esters of substituted benzoic acids is nicely described with the σ_I, $(\rho^\circ_R)_{ortho}$ and E_s^B constants (Tables III and IV). In alkaline hydrolysis of phenyl esters of substituted benzoic acids in water, the main factors responsible for the *ortho* substituent effect were found to be inductive ($(\rho_I)_{ortho}$ = 2.12) and steric (δ_{ortho} = 2.67) factors while the resonance factor appeared to be negligible ($(\rho^\circ_R)_{ortho}$ = 0.3). Figure 1 illustrates the dependence of the in-

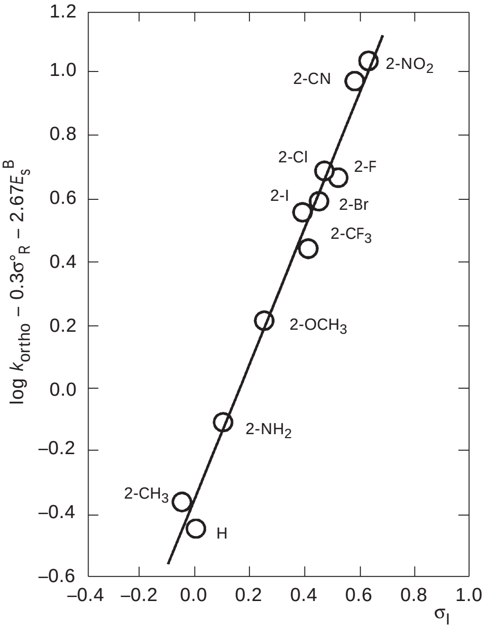


FIG. 1

The dependence of the inductive term (log $k - 0.3\sigma^\circ_R - 2.67E_s^B$) on σ_I values for alkaline hydrolysis of phenyl esters of *ortho*-substituted benzoic acids, $X\text{-}C_6H_4CO_2C_6H_5$, in water at 25 °C ductive term, represented as (log $k - 0.3\sigma°_R - 2.67E_S{}^B$) on the σ_I values for alkaline hydrolysis of phenyl esters of *ortho*-substituted benzoic acids in water. In the case of *ortho* substituents, the susceptibility to the inductive influence in phenyl and ethyl esters of substituted benzoic acids in water and 5% aqueous ethanol, respectively, was found to be ca. 1.3 times stronger than the inductive influence for *meta* and *para* substituents. In water, the *ortho* inductive effect from the acyl component of esters appeared to be 1.5 times higher than that from the phenyl component of esters.

In alkaline hydrolysis of phenyl esters of *ortho*-substituted benzoic acids the contribution of the steric effects in water (δ_{ortho} = 2.67) was found to be the same as in 50% aqueous DMSO (δ_{ortho} = 2.69, Table III). In alkaline hydrolysis of ethyl esters of *ortho*-substituted benzoic acids the values of δ_{ortho} appeared in the range from 1.9 to 3.1 (Table IV). In *ortho*-substituted phenyl benzoates, the steric effects in the acyl component of esters are ca. 2.7 times stronger than the steric effects from the phenyl component of esters (δ_{ortho} = 1.0, Table VI). In Fig. 2 the relationship between the steric effects in

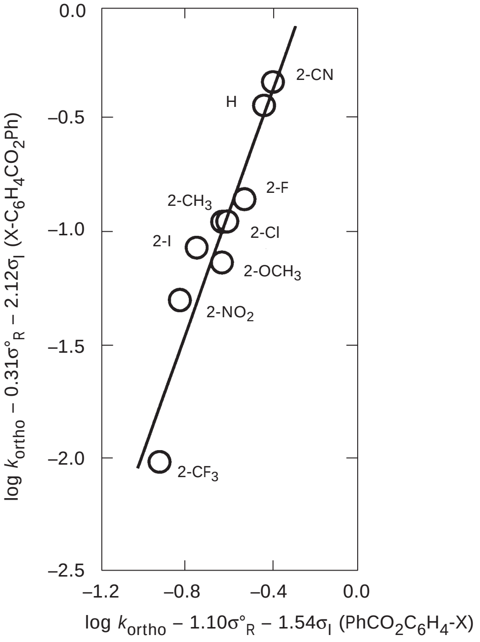


FIG. 2

Relationship between the steric effects in alkaline hydrolysis of phenyl esters of *ortho*-substituted benzoic acids, X-$C_6H_4CO_2C_6H_5$, calculated as log $k_{ortho} - 0.31\sigma°_R - 2.12\sigma_I$ and the steric effects in alkaline hydrolysis of *ortho*-substituted phenyl benzoates, $C_6H_5CO_2C_6H_4$-X, calculated as log $k_{ortho} - 1.10\sigma°_R - 1.54\sigma_I$ for water at 25 °C alkaline hydrolysis of phenyl esters of *ortho*-substituted benzoic acids, $X\text{-}C_6H_4CO_2C_6H_5$, represented as ($\log k_{\mathrm{ortho}} - 0.310.3\sigma^{\circ}_R - 2.12\sigma_I$) and the steric effects in alkaline hydrolysis of *ortho*-substituted phenyl benzoates, $C_6H_5CO_2C_6H_4\text{-}X$, calculated as ($\log k_{\mathrm{ortho}} - 1.10\sigma^{\circ}_R - 1.54\sigma_I$), for water at 25 °C is shown. Slope of this dependence is ca. 2.7.

When the Charton steric υ constants (Table VII) were used, the values of $(\rho)_{m,p}$, $(\rho^{\circ})_{m,p}$, $(\rho_I)_{\mathrm{ortho}}$ and $(\rho^{\circ}_R)_{\mathrm{ortho}}$ were found to be approximately the same as in the case of the E_s^B scale. Only in neat water $\delta_{\mathrm{ortho}} = -1.2$ for alkaline hydrolysis of phenyl esters of *ortho*-substituted benzoic acids (Table III) and $\delta_{\mathrm{ortho}} = -0.45$ for alkaline hydrolysis of *ortho*-substituted phenyl benzoates (Table VI). When the Charton steric υ constants were used, the steric effects in the acyl component of esters also appeared to be ca. 2.7 times stronger than the steric effects from the phenyl component of esters.

Effect of Solvent

The $\rho_{m,p}$ values calculated in the present work for alkaline hydrolysis of ethyl esters of *meta*- and *para*-substituted benzoic acids in 56% (w/w) aqueous acetone ($\rho_{m,p} = 2.33$), 85% (w/w) aqueous ethanol ($\rho_{m,p} = 2.54$) and 65% aqueous acetone ($\rho_{m,p} = 2.38$), appeared to be nearly the same as reported in the literature previously[9,10].

In alkaline hydrolysis of phenyl esters of substituted benzoic acids, the variation of the *meta* and *para* polar effect with solvent is comparable with that for ethyl benzoates. The polar effect of *meta* and *para* substituents in alkaline hydrolysis of phenyl esters of *meta*- and *para*-substituted benzoic acids at 25 °C increases by 0.6 units of ρ when going from neat water to 50% aqueous DMSO. In transition from 5% aqueous ethanol to 65% aqueous DMSO, the value of $\rho_{m,p}$ for alkaline hydrolysis of ethyl benzoates increases by 0.9 units of ρ.

When going from water to binary aqueous solvents, the difference between the *ortho* inductive and the *meta* and *para* inductive terms nearly disappears as the increase in the *ortho* inductive term due to solvent was found to be essentially lower than that of *meta* and *para* substituents (see Tables III and IV). Previously[5], in alkaline hydrolysis of substituted phenyl benzoates the variation of the *ortho* inductive term with the solvent electrophilicity was found to be 3 times smaller than that for *para* substituents.

The $(\rho^{\circ}_R)_{\mathrm{ortho}}$ values for phenyl and ethyl esters of *ortho*-substituted benzoic acids in transition from water to binary aqueous solvents appeared to increase approximately to the same extent as the resonance term of *para* derivatives, though the contribution of resonance in the case of *ortho* substituents in water was negligible (0.3 units of ρ). For alkaline hydrolysis of phenyl esters of substituted benzoic acids in pure water $\rho_{m,p} - (\rho^\circ_R)_{ortho}$ = 1.4, in 50% aqueous DMSO $\rho_{m,p} - (\rho^\circ_R)_{ortho}$ = 1.5. For ethyl esters of substituted benzoic acids in 5% aqueous ethanol, 56% aqueous acetone, 85% aqueous ethanol and 65% aqueous DMSO the values of $\rho_{m,p} - (\rho^\circ_R)_{ortho}$ were 1.3, 1.5, 1.3 and 1.2, respectively.

Steric Effects in Acid Hydrolysis and Esterification

The steric E°_s constants for *ortho* substituents proposed by Taft[14] gave excellent correlation using Eq. (*4*) (Table V):

$$E^\circ_s = 0.52(\pm 0.18) - 0.14(\pm 0.12)\sigma_I - 1.26(\pm 0.28)\sigma^\circ_R + 2.52(\pm 0.47)E_s^B \qquad (5)$$

$$R = 0.993,\ s = 0.062,\ s_o = 0.112,\ n = 7\ .$$

Similar to the Taft steric E°_s constants, the correlation of the log k values for acid esterification of substituted benzoic acids in methanol at 25 °C, acid hydrolysis of substituted methyl esters in 80% (v/v) aqueous methanol at 100.8 °C and in acid esterification of substituted benzoic acids in cyclohexanol at 55 °C with Eq. (*3*) (Table V) proved that the steric contribution in the acid esterification of *ortho*-substituted benzoic acids or in the acid hydrolysis of *ortho*-substituted benzoates (the value of δ_{ortho} ranging from 1.8 to 3.0) is approximately equal to the steric term in alkaline hydrolysis of esters of *ortho*-substituted benzoic acids (the mean value of δ_{ortho} is 2.6). This conclusion is in accordance with the Taft–Ingold assumption in establishing the Taft polar substituent constants scale, σ^*_o, for *ortho* substituents according to

$$\sigma^*_o = 1/2.48[\log (k/k_o)_B - \log (k/k_o)_A] \qquad (6)$$

where subscripts A and B refer to ester hydrolysis catalyzed by hydrogen ion and hydroxide ion, respectively.

A contribution of the resonance factor appeared to be significant in addition to steric effects in the Taft steric substituent constants E°_s ($(\rho^\circ_R)_{ortho}$ = –1.26, Eq. (*5*)), as well as in acid esterification of *ortho*-substituted benzoic acids and acid hydrolysis of esters of *ortho*-substituted benzoic acids (the value of $(\rho^\circ_R)_{ortho}$ in the range from –1.0 to –1.8) (Eq. (*5*), Table V). Consequently, the contribution of the resonance term in alkaline hydrolysis of esters of *ortho*-substituted benzoic acids (the $(\rho^\circ_R)_{ortho}$ value in the range 0–1.2) and in acid esterification of *ortho*-substituted benzoic acids or acid hydrolysis of *ortho*-substituted esters is quite different, even in sign. This is in good accordance with the mechanism of both reaction types considered: the electron donating substituents stabilize the positively charged complex in acid hydrolysis, but destabilize the negatively charged complex in alkaline hydrolysis. The value of $\rho_{m,p} - (\rho°_R)_{ortho} \approx 1.3$ for acid esterification of *ortho*-substituted benzoic acids and acid hydrolysis of *ortho*-substituted esters is nearly the same as that found for alkaline hydrolysis of esters of *ortho*-substituted benzoic acids (the $\rho_{m,p} - (\rho°_R)_{ortho}$ value in the range from 1.2 to 1.5). Equality of both steric effects and the values of $(\rho_{m,p} - (\rho°_R)_{ortho})$ in alkaline hydrolysis and acid hydrolysis once again shows that when calculating the Taft σ^*_o constants using the Ingold–Taft equation (*6*), the polar constant for *ortho* substituents, σ^*_o, does not contain any contribution of the steric effects and the overall contribution of the resonance effect becomes equal to that for *para* substituents.

Conclusions

In alkaline hydrolysis of phenyl and ethyl esters of *ortho*-, *meta*- and *para*-substituted benzoic acids the dependence of the reaction rates on the substituent effects was found to be precisely correlated with the Hammett–Charton equation (*3*) using for *meta* and *para* derivatives the Hammett polar substituent constants, $\sigma_{m,p}$, and for *ortho* derivatives the Taft inductive, σ_I, the resonance, $\sigma°_R$, and steric, E_s^B, or υ constants. $R > 0.99$ and $s < 0.1$ for the reaction series containing all *ortho*-substituted derivatives (X = F, Cl, Br, I, CH_3, CF_3, NO_2, OCH_3, NH_2, $N(CH_3)_2$, $C(CH_3)_3$) in neat water at 25 °C (Tables III and VI). From the acyl component of esters, the polar effect of *meta* and *para* substituents was found to be 1.6 times and the inductive effect of *ortho* substituents 1.5 times stronger than the corresponding influences from the aryl component. The resonance factor of *ortho* substituents in acyl component in water was found to be negligible ($\rho°_R = 0.3$). The contributions of the steric effects in alkaline hydrolysis of esters of *ortho*-substituted benzoic acids were approximately the same as in acid hydrolysis of esters of *ortho*-substituted benzoic acids and in acid esterification of *ortho*-substituted benzoic acids. In *ortho*-substituted phenyl benzoates the steric effects in the acyl component of esters were 2.7 times stronger than the steric effects from the aryl component of esters. This could be assigned to the non-planar *s-trans* conformation proposed for phenyl benzoates[43]. In phenyl esters the plane of phenyl ring in the aryl component assumed to be nearly perpendicular to the carbonyl bond plane and the phenyl plane in the acyl part of ester is coplanar with the carbonyl bond plane.

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