Variation of the temperature-dependent substituent effects with solvent in alkaline hydrolysis of substituted phenyl and alkyl benzoates and phenyl tosylates

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ABSTRACT: The second-order rate constants k for the alkaline hydrolysis of eight substituted alkyl benzoates have been measured spectrophotometrically in aqueous 5.3 M NaClO$_4$ and 0.5 M n-Bu$_4$NBr at various temperatures. Variation of the substituent effect with temperature in alkaline hydrolysis of *ortho-*, *meta-*, and *para*-substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates in various solvents (water, aqueous 0.5 M Bu$_4$NBr, 80% (v/v) DMSO, 2.25 M Bu$_4$NBr, and 5.3 M NaClO$_4$) was studied. The susceptibility to temperature variation of the *meta* and *para* polar substituent effect, the *ortho* inductive effect, and the alkyl polar effect for various media showed good correlation with the solvent electrophilicity, E_S, which characterizes the hydrogen-bond donating power of the solvent. The variation of the temperature-dependent *ortho* inductive effect with solvent hydrogen-bond donor capacity (electrophilicity) was found to be nearly twice smaller than that for *meta* and *para* polar effect. The temperature-dependent alkyl polar substituent effect was found to vary with E_S nearly by the same extent as the polar effect of *meta* and *para* substituents. The dependences of the ρ values (altogether 109 values of ρ) on the $(1/T)$ term for various media were found to cross nearly at the same isosolvent temperature $(1/\beta_{\mathrm{isosolv}} \approx 2 \times 10^{-3})$ for *meta-*, *para-*, *ortho-*, and alkyl-substituted esters. At $T = \beta_{\mathrm{isosolv}}$ the difference $(\rho)_S - (\rho)_{\mathrm{Water}}$ becomes zero for all polar substituent effects in all media considered and the additional inductive effect from the *ortho* position (compared with *para* derivatives) disappears for all solvents studied. Copyright © 2007 John Wiley & Sons, Ltd.
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KEYWORDS: esters; alkaline hydrolysis; substituent effects; kinetics; isoparametric relationships

INTRODUCTION

The aim of the present work was to study the variation of the temperature-dependent polar substituent effects with solvent in the alkaline hydrolysis of *ortho-*, *meta-*, and *para*-substituted phenyl benzoates, C$_6$H$_5$CO$_2$C$_6$H$_4$—X, phenyl tosylates, 4-CH$_3$—C$_6$H$_4$SO$_2$OC$_6$H$_4$—X, and alkyl benzoates, C$_6$H$_5$CO$_2$R, including kinetic data for water, aqueous 0.5 M Bu$_4$NBr, 80% (v/v) DMSO, 2.25 M Bu$_4$NBr, and 5.3 M NaClO$_4$.

Recently[1–3] we studied the importance of different solvent parameters for substituent effects in alkaline hydrolysis of *ortho-*, *meta-*, and *para*-substituted phenyl benzoates, phenyl tosylates, and in substituted alkyl benzoates at 50 °C. The solvent electrophilicity, ΔE_S,[4–9] which measures the hydrogen-bond donating power of the solvent, was found to be the main factor responsible for the changes in the *ortho*, *meta*, and *para* as well as in the *alkyl* polar substituent effects with medium. In our previous works kinetics of the alkaline hydrolysis of *ortho-*, *meta-*, and *para*-substituted phenyl benzoates and phenyl tosylates has been studied dependent on temperature in pure water, aqueous 0.5 M Bu$_4$NBr, 2.25 M Bu$_4$NBr, 80% (v/v) DMSO and 5.3 M NaClO$_4$ and *alkyl*-substituted benzoates, C$_6$H$_5$CO$_2$R, in water, aqueous 2.25 M Bu$_4$NBr, and 80% (v/v) DMSO (see Refs. [10–16] and references cited therein). Previously[3] the kinetics of alkyl benzoates in aqueous 0.5 M Bu$_4$NBr and 5.3 M NaClO$_4$ was measured at 25 and 50 °C. In the present work the second-order rate constants for the

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alkaline hydrolysis of substituted alkyl benzoates (R = CH_3, C_2H5, CH_2Cl, CH_2CN, $CH_2C{\equiv}CH$, $CH_2C_6H_5$, CH_2CH_2Cl, $CH_2CH_2OCH_3$,) in aqueous 0.5 M Bu_4NBr at 15 and 40 °C and for aqueous 5.3 M $NaClO_4$ were measured at 15, 25, 40, and 50 °C. The former medium has been known[8,13] to have lower H-bond donor capacity than water whereas aqueous 5.3 M $NaClO_4$ has higher H-bond donating power than pure water.

The use of the ionic solvent as media should enable further to include the esters with charged substituents in the same data set besides esters with electroneutral substituents. Earlier the kinetics of the alkaline hydrolysis of substituted phenyl tosylates, phenyl and alkyl benzoates with charged substituents ($N(CH_3)_3^+$, O^-, COO^-, SO_3^-) has been measured in pure water and dependent on additions of NaCl (see Refs. [17–21] and references cited therein).

In the previous papers to study the substituent effects dependent on temperature, the log$k$ for the alkaline hydrolysis *ortho*-, *meta*-, and *para*-substituted phenyl benzoates,[10–12] and phenyl tosylates[2,16] in some aqueous solvents at various temperatures were treated according to the modified Fujita and Nishioka[22] equation:

$$\log k_{m,p,ortho}$$
$$= \log k_o + c_{1(m,p,ortho)}\sigma^\circ + c_{2(ortho)}\sigma_I$$
$$+ c_{3(ortho)}E_s^B + c_4\left(\frac{1}{T}\right) + c_{5(m,p,ortho)}\left(\frac{1}{T}\right)\sigma^\circ$$
$$+ c_{6(ortho)}\left(\frac{1}{T}\right)\sigma_I \qquad (1)$$

and

$$\rho_T = a + b\left(\frac{1}{T}\right) \qquad (2)$$

In Eqn (1) in the case of *ortho* substituents the additional $c_{2(ortho)}\sigma_I$, $c_{3(ortho)}E_s^B$, and $c_{6(ortho)}(1/T)\sigma_I$ terms were included. In alkaline hydrolysis of *ortho*-substituted phenyl tosylates the influence of the steric factor was considered negligible and the term $c_{3(ortho)}E_s^B$ was omitted. It was found[2,10,16] in both the alkaline hydrolysis of substituted phenyl benzoates and phenyl tosylates in water and aqueous 0.5 M Bu_4NBr that the additional inductive effect from the *ortho* position (compared with *para* derivatives) turned zero at $T \approx 500$ K in the case of all substituents.

In Eqn (1) the dependence of substituent effects on temperature or the dependence of activation energy on substituent effects in a given solvent is characterized by the values of reaction constant $c_{5(m,p)}$ in cross terms $(1/T)\sigma^\circ$ and the values of b in Eqn (2):

$$-2.3Rc_{5(m,p)} = -2.3Rb_{(m,p)} = \frac{(E_X - E_H)_{m,p}}{\sigma^\circ} \qquad (3)$$

In Eqn (3) E_X and E_H are the activation energies for the substituted and non-substituted derivatives, respectively, in the medium considered. The substituent-dependent activation energy for *ortho* derivatives in Eqn (1) was assumed to be different from that for *meta* and *para* derivatives:

$$-2.303R\left(c_{5(m,p,ortho)} + c_{6(ortho)}\right)$$
$$= \frac{(E_X - E_H)_{m,p,ortho}}{(\sigma^\circ)_{m,p}} + \frac{(E_X - E_H)_{ortho}}{\sigma_I} \qquad (4)$$

The purpose of the present work was to study the *meta* and *para* polar, *ortho* inductive, and alkyl polar effects dependent on both the temperature and solvent in the alkaline hydrolysis of substituted benzoates and tosylates. For that aim we checked how the temperature-dependent and the temperature-independent *meta* and *para* polar, *ortho* inductive, and alkyl polar effects or the corresponding substituent-dependent enthalpy and entropy terms in the alkaline hydrolysis of *ortho*-, *meta*-, and *para*-substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates in various solvents (water, aqueous 0.5 M Bu_4NBr, 80% (v/v) DMSO, 2.25 M Bu_4NBr, and 5.3 M $NaClO_4$) vary with the solvent electrophilicity, E_S, which either increases (aqueous 5.3 M $NaClO_4$) or decreases (aqueous Bu_4NBr and DMSO) while going from water to another media. One might expect that the influence of this factor is mediated by the hydrogen-bond donor-like specific solvatation of the transition state and OH^- ion as reagent in the alkaline hydrolysis of esters by the hydroxylic solvent. The other aim was to compare the isosolvent relationship with respect to temperature variation (isosolvent relationship (ISoR)) and isokinetic temperatures in various solvents (isokinetic relationship (IKR)) for the *meta* and *para* polar, *ortho* inductive, and alkyl polar substituent effects in the alkaline hydrolysis of benzoates and tosylates.

It was of interest to compare how the substituent effects vary simultaneously with both temperature and the solvent electrophilicity, E_S, in alkaline hydrolysis substituted phenyl benzoates, $C_6H_5CO_2C_6H_4$—X, and the alkaline hydrolysis of substituted phenyl tosylates, $4\text{-}CH_3\text{-}C_6H_4SO_2OC_6H_4$—X. At constant temperature the *meta* and *para* polar and the *ortho* inductive effects in alkaline hydrolysis of substituted phenyl benzoates and tosylates were found to vary with the solvent electrophilicity, E_S, approximately by the same extent[1,2] though the polar effect of substituents in both reaction series considered in water exhibited a twofold difference: $\rho^\circ_{(m,p)Tos}/\rho^\circ_{(m,p)Benz} = \rho_{I(ortho)Tos}/\rho_{I(ortho)Benz} \approx 2$.

The activation free energy due to substituent effect could be written as the sum of activation entropy and activation enthalpy terms[23–30]:

$$\delta\Delta G^\ddagger = \delta\Delta H^\ddagger - T\delta\Delta S^\ddagger \qquad (5)$$

$\delta\Delta G^{\ddagger} = \Delta G^{\ddagger} - \Delta G_0^{\ddagger}$, $\delta\Delta H^{\ddagger} = \Delta H^{\ddagger} - \Delta H_0^{\ddagger}$, and $\delta\Delta S^{\ddagger} = \Delta S^{\ddagger} - \Delta S_0^{\ddagger}$. $\Delta G^{\ddagger}$, $\Delta H^{\ddagger}$, $\Delta S^{\ddagger}$ and $\Delta G_0^{\ddagger}$, $\Delta H_0^{\ddagger}$, $\Delta S_0^{\ddagger}$ are the activation parameters for the substituted and unsubstituted compounds. Equation (6) is called the IKR and the ratio of $\delta\Delta H^{\ddagger}$ and $\delta\Delta S^{\ddagger}$ is equal to the isokinetic temperature, β [25–42]

$$\frac{\delta\Delta H^{\ddagger}}{\delta\Delta S^{\ddagger}} = \beta \tag{6}$$

At isokinetic temperature, β, all reactions of the series in a given solvent should proceed with the same rate ($\rho = 0$). The ISoR with respect to temperature[26,29,30,37–41] could be expressed by Eqn (7):

$$\frac{\delta\Delta H_S^{\ddagger} - \delta\Delta H_W^{\ddagger}}{\delta\Delta S_S^{\ddagger} - \delta\Delta S_W^{\ddagger}} = \beta_{\text{isosolv}} \tag{7}$$

In Eqn (7) S denotes a solvent considered and W denotes water chosen as standard solvent in the present work. At the isosolvent temperature, β_{isosolv}, the substituent effects in all solvents considered turn equal to each other. It follows from the theoretical considerations[26,27–29,42] that the common value of β is the rigid proof of the homogeneity of interaction.

From the Eyring[23,24] activated complex theory and Arrhenius equation it follows that the values of $\Delta H^{\ddagger}$, $\Delta S^{\ddagger}$, activation energy, E, and $\log A$ values are related by Eqns (8) and (9):

$$\Delta H^{\ddagger} = E - RT \tag{8}$$

$$\Delta S^{\ddagger} = 2.303(\log A - \log T - 10.75) \tag{9}$$

In the present work to study the IKR and ISoR we did not use the values of the activation energies, E, and $\log A$, calculated with the Arrhenius equation, because in the case of *ortho* and alkyl derivatives they reflect the gross influence of the inductive, resonance, and steric effects. The substituent-dependent enthalpy and entropy components in the alkaline hydrolysis of *ortho*-, *meta*-, and *para*-substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates were separated using the multilinear Eqns (10)–(12). The isokinetic temperatures and isosolvent temperatures for the *meta* and *para* polar, *ortho* inductive, and alkyl polar effects were calculated from the corresponding reaction constants c in the multilinear relationship with cross terms (Eqns (10)–(12) and (20)) using the principles of isoparametricity.[27,32]

EXPERIMENTAL

The preparation procedure and characteristics of substituted alkyl benzoates, $C_6H_5CO_2R$, the technique of kinetic measurements as well as purification of reagents were described earlier.[14,43] As alkali, aqueous

0.0374 M Bu_4NOH was used for the kinetic measurements in aqueous 0.5 M Bu_4NBr and 0.0386 M NaOH in aqueous 5.3 M $NaClO_4$. For kinetic measurements in aqueous 0.5 M Bu_4NBr and 5.3 M $NaClO_4$ the spectrophotometric method was used.[14] The second-order rate constants k were calculated by dividing the pseudo-first-order rate constants k_1 by the alkali concentration. The measurements were repeated and the arithmetic means of the corresponding second-order rate constants k were calculated.

The second-order rate constants, k ($dm^3\,mol^{-1}\,s^{-1}$), for the alkaline hydrolysis of substituted alkyl benzoates, $C_6H_5CO_2R$, in 0.5 M Bu_4NBr at 15 and 40 and 60 °C and in aqueous 5.3 M $NaClO_4$ at 15, 25, 40, and 50 °C, the wavelength, λ, used in the spectrophotometric kinetic measurements, and the number of measurements are given in Table 1. The values of $\log A$ and activation energies, E ($kJ\,mol^{-1}$) for the alkaline hydrolysis of substituted alkyl benzoates in aqueous 0.5 M Bu_4NBr and 5.3 M $NaClO_4$ calculated with Arrhenius equation ($\log k = \log A - E/2.3RT$) are listed in Table S1.

DATA PROCESSING AND RESULTS

For the study of variation of the substituent effects with temperature, the $\log k$ values for alkaline hydrolysis of *ortho*-, *meta*-, and *para*-substituted phenyl benzoates, $C_6H_5CO_2C_6H_4$—X, phenyl tosylates, 4-CH_3—$C_6H_4SO_2OC_6H_4$—X, and alkyl benzoates, $C_6H_5CO_2R$, in water, aqueous 5.3 M $NaClO_4$, 0.5 M Bu_4NBr, 2.25 M Bu_4NBr, and 80% (v/v) DMSO were treated according to the following multilinear relationships:[5,13,16,27,32,44]

$T \neq$ const, X $\neq$ const:

$$\log k_{m,p} = c_o + c_{1(m,p)}\sigma^{\circ} + c_2\left(\frac{1}{T}\right)$$
$$+ c_{3(m,p)}\left(\frac{1}{T}\right)\sigma^{\circ} \tag{10}$$

$$\log k_{ortho} = c_o + c_{1(ortho)}\sigma_I + c_{2(ortho)}\sigma_R^{\circ}$$
$$+ c_{3(ortho)}E_s^B + c_4\left(\frac{1}{T}\right)$$
$$+ c_{5(ortho)}\left(\frac{1}{T}\right)\sigma_I + c_{6(ortho)}\left(\frac{1}{T}\right)\sigma_R^{\circ} \tag{11}$$

$$\log k_{Alk} = c_o + c_{1(Alk)}\sigma_I + c_{2(Alk)}E_s^B + c_3\left(\frac{1}{T}\right)$$
$$+ C_{4(Alk)}\left(\frac{1}{T}\right)\sigma_I \tag{12}$$

For comparison, the values of ρ in water, aqueous 5.3 M $NaClO_4$, 0.5 M Bu_4NBr, 2.25 M Bu_4NBr, and 80%

Table 1. The second-order rate constants k ($dm^3 mol^{-1} s^{-1}$) for the alkaline hydrolysis of substituted alkyl benzoates, $C_6H_5CO_2R$, in aqueous 0.5 M Bu_4NBr and 5.3 M $NaClO_4$ at various temperatures[a]

R	T (°C)	k ($dm^3 mol^{-1} s^{-1}$) in 0.5 M Bu_4NBr	$\log k$	n	k ($dm^3 mol^{-1} s^{-1}$) in 5.3 M $NaClO_4$	$\log k$	n
$ClCH_2$	50	4.79 ± 0.24[b]	0.680	5	2.16 ± 0.07	0.334	3
	40	2.61 ± 0.12	0.417	4	1.22 ± 0.01	0.086	3
	25	1.27 ± 0.09[b]	0.104	3	0.463 ± 0.007[b]	−0.334	3
	15	0.708 ± 0.002	−0.150	3	0.187 ± 0.004	−0.728	3
$NCCH_2$	50	5.36 ± 0.25[b]	0.728		1.90 ± 0.12	0.279	3
	40	3.32 ± 0.29	0.521	3	1.00 ± 0.03	0	3
	25	1.58 ± 0.11[b]	0.199	3	0.399 ± 0.012[b]	−0.399	3
	15	0.975 ± 0.009	−0.011	3	0.167 ± 0.005	−0.777	3
$HC{\equiv}CCH_2$	50	0.554 ± 0.003[b]	−0.256	5	0.285 ± 0.010	−0.545	3
	40	0.297 ± 0.003	−0.527	3	0.141 ± 0.010	−0.851	3
	25	0.134 ± 0.001[b]	−0.873	3	0.0531 ± 0.0014[b]	−1.275	3
	15	0.0676 ± 0.0007	−1.170	3	0.0195 ± 0.0001	−1.710	3
$Cl(CH_2)_2$	50	0.276 ± 0.001[b]	−0.559	4			
	40	0.140 ± 0.002	−0.854	3			
	25	0.0549 ± 0.0004[b]	−1.260	4			
	15	0.0307 ± 0.0011	−1.513	3			
$CH_3O(CH_2)_2$	60	0.287 ± 0.004	−0.542	3			
	50	0.143 ± 0.002[b]	−0.845	3	0.0777 ± 0.0006	−1.110	3
	40	0.0989 ± 0.0050	−1.005	3	0.0386 ± 0.0006	−1.413	3
	25	0.0325 ± 0.0017[b]	−1.488	3	0.0125 ± 0.0001	−1.903	3
	15	0.0172 ± 0.0002	−1.765	3	0.00446 ± 0.00023	−2.351	3
$PhCH_2$	60	0.216 ± 0.002	−0.665	4			
	50	0.110 ± 0.001[b]	−0.959	4			
	40	0.0619 ± 0.0004	−1.208	3			
	25	0.0233 ± 0.0002[b]	−1.633	4			
	15	0.0126 ± 0.0006	−1.900	3			
CH_3	60	0.300 ± 0.001	−0.523	4			
	50	0.158 ± 0.002[b]	−0.801	3	0.0845 ± 0.0021	−1.073	3
	40	0.0972 ± 0.0030	−1.012	4	0.0389 ± 0.0015	−1.410	3
	25	0.0339 ± 0.0002	−1.470	5	0.0136 ± 0.0007	−1.866	3
	15	0.0170 ± 0.0010	−1.770	4	0.00454 ± 0.00052	−2.343	3
CH_3CH_2	50	0.0640 ± 0.0010[b]	−1.194	4			
	40	0.0389 ± 0.0016	−1.410	3			
	25	0.0130 ± 0.0004[b]	−1.886	4			
	15	0.00602 ± 0.00012	−2.220	3			

[a] As alkali, aqueous 0.0374 M Bu_4NOH was used for the kinetic measurements in aqueous 0.5 M Bu_4NBr and 0.0386 M NaOH in aqueous 5.3 M $NaClO_4$. The wavelength, λ, used in the spectrophotometric kinetic measurements was 240 *nm* for all alkyl benzoates. n equals the number of kinetic measurements used in determination of the arithmetic mean value of the second-order rate constants k.
[b] The k values reported earlier.[3]

(v/v) DMSO at various temperatures were correlated with Eqns (13)–(15):

$$\rho^{\circ}_{m,p} = a_{m,p} + b_{m,p}\left(\frac{1}{T}\right) \tag{13}$$

$$\rho_{I(ortho)} = a_{I(ortho)} + b_{I(ortho)}\left(\frac{1}{T}\right) \tag{14}$$

$$\rho_{I(Alk)} = a_{I(Alk)} + b_{I(Alk)}\left(\frac{1}{T}\right) \tag{15}$$

In Eqns (10)–(12) and (13)–(15):

$c_{1(m,p)} = a_{m,p}$, $c_{3(m,p)} = b_{m,p}$, $c_{1(ortho)} = a_{I(ortho)}$,
$c_{5(ortho)} = b_{I(ortho)}$, $c_{1(Alk)} = a_{I(Alk)}$, $c_{4(Alk)} = b_{I(Alk)}$

To study the influence of the solvent electrophilicity, E_S, on the susceptibilities of the *meta* and *para* polar ($c_{3(m,p)}$), the *ortho* inductive ($c_{5(ortho)}$), and the alkyl polar ($c_{4(Alk)}$) substituent effects to temperature variation, Eqns (16) and (17) were used:

$$c = m_o + m_1 \Delta E_S \tag{16}$$

$$b = m_o + m_1 \Delta E_S \tag{17}$$

where $c = c_{3(m,p)}$, $c_{5(ortho)}$, $c_{4(Alk)}$ in cross terms $c_{3(m,p)}$ $(1/T)\sigma^{\circ}$, $c_{5(ortho)}(1/T)\sigma_I$, and $c_{4(Alk)}(1/T)\sigma_I$, respectively in Eqns (10)–(12) and $b = b_{m,p}$, $b_{I(ortho)}$, and $b_{I(Alk)}$ in Eqns (13)–(15).

The variation of the temperature-independent terms of the *meta* and *para* polar ($c_{1(m,p)}$), the *ortho* inductive ($c_{1(ortho)}$), and the alkyl polar ($c_{1(Alk)}$) substituent effect

(or the corresponding substituent-dependent entropy terms) in various media were correlated with Eqns (18) and (19):

$$c = p_o + p_1 \Delta E_S \tag{18}$$

$$a = p_o + p_1 \Delta E_S \tag{19}$$

In Eqns (18) and (19) the values of $c = c_{1(m,p)}$, $c_{1(ortho)}$, $c_{1(Alk)}$ in Eqns (10)–(12) and $a = a_{I(m,p)}$, $a_{I(ortho)}$, $a_{I(Alk)}$ in Eqns (13)–(15) were used.

Similarly, to study the variation of the substituent effects simultaneously with temperature and medium, the ρ values in various solvents and at various temperatures were used:

$$\rho_{TS} = c_0 + c_1\left(\frac{1}{T}\right) + c_2\Delta E_S + c_3\left(\frac{1}{T}\right)\Delta E_S \tag{20}$$

Equations (10)–(12) with cross terms take into account simultaneously the influence of the substituent effect and temperature. The influence of solvent was studied separately with Eqns (16)–(19). Equation (20) takes into account the influence of both the temperature and solvent effects when the ρ values in various solvents and at various temperatures are involved.

In Eqn (20) $\rho_0 = 0$ for the *meta* and *para* polar effect in alkaline hydrolysis of substituted phenyl benzoates and tosylates and alkyl benzoates as in standard medium (pure water) reaction series considered were found to be isoentropic. In Eqns (16)–(19) and (20): $m_0 = c_1$, $m_1 = c_3$, $p_o = c_0$, and $p_1 = c_2$.

Equation (20) is a multilinear relationship with cross terms, which enables to calculate the isosolvent temperature at which the ρ value (i.e. susceptibility to substituent effect) is the same in all solvents. We calculated the isosolvent effect temperature $\beta_{isosolv}$ from Eqn (20) using the isoparametricity principles of Palm and Istomin[5,27,32]

$$\frac{1}{\beta_{isosolv}} = \frac{-c_2}{c_3} \tag{21}$$

and from the relation of the susceptibilities of the temperature-dependent (i.e., the substituent-dependent enthalpy term) and the temperature-independent (i.e. the substituent-dependent entropy term) substituent effects to the solvent electrophilicity, ΔE_S (Eqns (16)–(19):

$$\beta_{isosolv} = \frac{-m_1}{p_1} \tag{22}$$

The isokinetic temperature β for alkaline hydrolysis substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates was calculated separately for the *meta* and *para* polar effect, *ortho* inductive effect, and alkyl polar effect in various media (water, aqueous 5.3 M NaClO$_4$, 0.5 M Bu$_4$NBr, 2.25 M Bu$_4$NBr, and 80% (v/v) DMSO).The isokinetic temperature for various media was calculated using reaction constants c in Eqns

(10)–(12):[15,16,23]

$$\beta_{m,p} = \frac{c_{3(m,p)}}{c_{1(m,p)}} \tag{23}$$

$$\beta_{ortho-ind} = \frac{c_{5(ortho)}}{c_{1(ortho)}} \tag{24}$$

$$\beta_{Alk} = \frac{c_{4(Alk)}}{c_{1(Alk)}} \tag{25}$$

and from Eqns (13)–(15)

$$\beta_{m,p} = \frac{b_{m,p}}{a_{m,p}} \tag{26}$$

$$\beta_{ortho-ind} = \frac{b_{I(ortho)}}{a_{I(ortho)}} \tag{27}$$

$$\beta_{Alk} = \frac{b_{I(Alk)}}{a_{I(Alk)}} \tag{28}$$

The Taft's polar σ°,[44,45] inductive σ_I,[46] the resonance $\sigma_R{}^{\circ}$ $[\sigma_R{}^{\circ} = (\sigma^{\circ})_{para} - \sigma_I]$[47] scales, and steric E_s^B constants[2,11,13] were used at the data processing. For *ortho* substituents: $E_s^B = \log k_H+^X - \log k_H+^H$, where k_H+^X and k_H+^H are the rate constants for the acidic hydrolysis of *ortho*-substituted and unsubstituted phenyl benzoates in water at 50 °C.[48] The steric constants for the variable substituent in the alcohol component of ester, E_s^B were calculated as follows: $E_s^B = \log k_H+^R - \log k_H+^{CH3}$, where k_H+^R and k_H+^{CH3} are the rate constants for acid hydrolysis of R-substituted and CH$_3$-substituted alkyl benzoate, C$_6$H$_5$CO$_2$R, or acetate, CH$_3$CO$_2$R, in water.[3,14] As the solvent characteristic, its H-bond donating power (electrophilicity) E_S values of Koppel and Palm[4–9] were used, $\Delta E_S = E_S - E_{H_2O}$. The standard medium where ΔE_S is equal to zero is pure water and the standard substituent is X = H. The data processing was carried out using a multiple-parameter linear least-squares (LLSQ) procedure.[49] Significantly deviating points were excluded using a Student criterion. The exclusion of the significantly deviating points was performed on different confidence levels of the *t*-test.

The results of the correlation with Eqns (10)–(15) for the alkaline hydrolysis of substituted phenyl benzoates, alkyl benzoates, and for substituted phenyl tosylates in water, aqueous 5.3 M NaClO$_4$, 0.5 M Bu$_4$NBr, 2.25 M Bu$_4$NBr, and 80% (v/v) DMSO are presented in Tables S2–S5. The values of $\rho^{\circ}_{m,p}$, $\rho_{I(ortho)}$, and $\rho_{I(Alk)}$ for the alkaline hydrolysis of substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates in water, aqueous 5.3 M NaClO$_4$, 0.5 M Bu$_4$NBr, 2.25 M Bu$_4$NBr, and 80% (v/v) DMSO at various temperatures used in correlations with Eqns (13)–(15) and (20) are listed in Table S6. The results of correlation of the $c_{3(m,p)}$, $c_{5(ortho)}$, $c_{4(Alk)}$, $b_{m,p}$, $b_{I(ortho)}$, and $b_{I(Alk)}$ values with Eqns (16) and (17), the $c_{1(m,p)}$, $c_{1(ortho)}$, $c_{1(Alk)}$, $a_{m,p}$, $a_{I(ortho)}$, and $a_{I(Alk)}$ values with Eqns (18) and (19), correlation of $\rho^{\circ}_{m,p}$, $\rho_{I(ortho)}$, and $\rho_{I(Alk)}$ with Eqn (20), and the values of $\beta_{isosolv}$ determined with Eqns (21) and (22) are shown in Table 2.

Table 2. Correlation of the temperature-dependent (i.e., enthalpy terms) and the temperature-independent (i.e., entropy terms) *meta* and *para* polar, *ortho* inductive, and alkyl polar effects with the solvent electrophilicity parameters, ΔE_S, in the alkaline hydrolysis of substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates using Eqns (16) and (20)[a]

Correlation with $c=m_0+m_1\Delta E_S$ and $c=p_0+p_1\Delta E_S$ in Eqns (16)–(19)

	$c=c_{3(m,p)}$, $c_{5(ortho)}$, $c_{2(Alk)}$ Equation (16)	$c=b_{m,p}$, $b_{I(ortho)}$, $b_{I(Alk)}$ Equation (17)	$c=c_1$ Equation (18)	$c=a_{m,p}$, $a_{I(ortho)}$, $a_{I(Alk)}$ Equation (19)	Correlation with $\rho_{TS}=c_0+c_1\left(\frac{1}{T}\right)+c_2\Delta E+c_3\left(\frac{1}{T}\right)\Delta E$ Equation (20)	
	Meta- and *para*-substituted phenyl benzoates					
$p_{0(m,p)}$			-0.151 ± 0.178	-0.251 ± 0.109	c_0	0
$m_{0(m,p)}$	393.2 ± 92.2	418.0 ± 48.6			$c_{1(m,p)}$	340.9 ± 9.5
$p_{1(m,p)}$			0.114 ± 0.020	0.115 ± 0.012	$c_{2(m,p)}$	0.0902 ± 0.0532
$m_{1(m,p)}$	-53.7 ± 9.2	-53.6 ± 5.3			$c_{3(m,p)}$	-46.4 ± 16.1
n/n_0	5/5	5/5	5/5	5/5	n/n_0	23/23
R	0.944	0.981	0.944	0.979		
S	146	84.7	0.309	0.190	s	117
s_0	0.329	0.168	0.328	0.206	s_0	0.231
$\beta_{isosolv}$			471 K	466 K		514 K
$1/\beta_{isosolv}$			2.14×10^{-3}	2.15×10^{-3}		1.95×10^{-3}
	Ortho-substituted phenyl benzoates					
$p_{0(ortho)}$			-0.668 ± 0.088	-0.858 ± 0.056	c_0	-0.898 ± 0.781
$m_{0(ortho)}$	675.2 ± 37.2	772.2 ± 30.1			$c_{1(ortho)}$	737.0 ± 131.1
$p_{1(ortho)}$			0.0660 ± 0.0100	0.0454 ± 0.0062	$c_{2(ortho)}$	0.0568 ± 0.0522
$m_{1(ortho)}$	-29.9 ± 4.1	-24.9 ± 3.3			$c_{3(ortho)}$	-28.4 ± 16.0
n/n_0	5/5	5/5	5/5	5/5	n/n_0	24/24
R	0.964	0.966	0.958	0.964		0.968
S	64.8	52.4	0.154	0.099	s	83.0
s_0	0.265	0.258	0.285	0.267	s_0	0.258
$\beta_{isosolv}$			453 K	548 K		499.6 K
$1/\beta_{isosolv}$			2.20×10^{-3}	1.82×10^{-3}		2.00×10^{-3}
	Meta- and *para*-substituted phenyl tosylates					
$p_{0(m,p)}$			-0.267 ± 0.113	-0.106 ± 0.076	c_0	0
$m_{0(m,p)}$	744.0 ± 60.1	780.3 ± 68.3			$c_{1(m,p)}$	650.6 ± 16.4
$p_{1(m,p)}$			0.128 ± 0.012	0.106 ± 0.076	$c_{2(m,p)}$	0.106 ± 0.076
$m_{1(m,p)}$	-59.3 ± 7.3	-58.0 ± 7.5			$c_{3(m,p)}$	-54.9 ± 25.0
n/n_0	5/5	5/5	5/5	5/5	n/n_0	21/21
R	0.971	0.968	0.981	0.968		
S	115	251	0.196	0.260	s	188.0
s_0	0.237	0.251	0.190	0.268	s_0	0.370
$\beta_{isosolv}$			463 K	547 K		518 K
$1/\beta_{isosolv}$			2.16×10^{-3}	1.82×10^{-3}		1.93×10^{-3}
	Ortho-substituted phenyl tosylates					
$p_{0(m,p)}$			-1.711 ± 0.034	-1.646 ± 0.207	c_0	-1.543 ± 0.736
$m_{0(m,p)}$	1551 ± 41	1447 ± 71			$c_{1(m,p)}$	1485 ± 145
$p_{1(m,p)}$			0.0590 ± 0.0037	0.0549 ± 0.0206	$c_{2(m,p)}$	0.0501 ± 0.0495
$m_{1(m,p)}$	-28.6 ± 4.3	-31.8 ± 7.8			$c_{3(m,p)}$	-25.8 ± 16.2
n/n_0	5/5	5/5	5/5	4/5	n/n_0	21/21
R	0.952	0.886	0.992	0.817	R	0.969
S	71	124	0.0592	0.575	s	93.0
s_0	0.306	0.451	0.126	0.242	s_0	0.247
$\beta_{isosolv}$			485 K	580 K		515 K
$1/\beta_{isosolv}$			2.06×10^{-3}	1.72×10^{-3}		1.94×10^{-3}
	Alkyl-substituted benzoates					
$p_{0(Alk)}$			-0.186 ± 0.084	0.298 ± 0.092	c_0	0
$m_{0(Alk)}$	1196 ± 52	1208 ± 44			$c_{1(Alk)}$	1136 ± 11
$m_{1(Alk)}$			0.0771 ± 0.0092	0.0790 ± 0.0100	$c_{2(Alk)}$	0.113 ± 0.071
$m_{1(Alk)}$	-43.9 ± 5.7	-43.2 ± 4.8			$c_{3(Alk)}$	-51.6 ± 21.6

(Continues)

Table 2. (Continued)

Correlation with $c = m_0 + m_1 \Delta E_S$ and $c = p_0 + p_1 \Delta E_S$ in Eqns (16)–(19)

	$c = c_{3(m,p)}$, $c_{5(ortho)}$, $c_{2(Alk)}$ Equation (16)	$c = b_{m,p}$, $b_{I(ortho)}$, $b_{I(Alk)}$ Equation (17)	$c = c_1$ Equation (18)	$c = a_{m,p}$, $a_{I(ortho)}$, $a_{I(Alk)}$ Equation (19)		Correlation with $\rho_{TS} = c_0 + c_1\left(\frac{1}{T}\right)$ $+ c_2\Delta E + c_3\left(\frac{1}{T}\right)\Delta E$ Equation (20)
n/n_0	5/5	5/5	5/5	5/5	n/n_0	21/21
R	0.962	0.975	0.972	0.969		
S	91.2	76.8	0.147	0.159	s	131
s_0	0.273	0.220	0.235	0.249	s_0	0.274
$\beta_{isosolv}$			569 K	547 K		456 K
$1/\beta_{isosolv}$			1.75×10^{-3}	1.82×10^{-3}		2.19×10^{-3}

The values of the isosolvent temperatures are calculated as $\beta_{isosolv} = -m_1/p_1$ and $\beta_{isosolv} = -c_3/c_2$.
[a] The values of $c = c_{3(m,p)}$, $c_{5(ortho)}$, $c_{2(Alk)}$ c_1 in Tables S2 and S3, the values of a and b in Tables S4 and S5, and the values of ρ_{TS} in Table S6 for water, aqueous 5.3 M NaClO$_4$, 0.5 M Bu$_4$NBr, 2.25 M Bu$_4$NBr, and 80% (v/v) DMSO were used.

The values of isokinetic temperature, β, for alkaline hydrolysis of substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates in various media calculated with Eqns (23)–(28) are collected in Table 3.

DISCUSSION

Both the reaction constant, c, in cross terms $c(1/T)\sigma$ (Eqns (10)–(12)) and the value of b in Eqns (13)–(15) characterize the susceptibility of the corresponding substituent effect to temperature variation in a medium considered. In pure water, the value of $c_{3(m,p)}$ in cross term $c_{3(m,p)}(1/T)\sigma^\circ$ in Eqn (10) and $b_{m,p}$ in Eqn (13), characterizing the susceptibility of the *meta* and *para* polar effect to temperature variation in alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4$—X, are equal to 0.33×10^3 and 0.32×10^3, respectively (Tables S2 and

S4). The corresponding values for alkaline hydrolysis of substituted phenyl tosylates, 4-CH$_3$—C$_6$H$_4$SO$_2$OC$_6$H$_4$—X, in pure water are: $c_{3(m,p)} = 0.60 \times 10^3$ and $b_{m,p} = 0.62 \times 10^3$ (Tables S3 and S5). The $c_{3(m,p)}$ and $b_{m,p}$ values increase by *ca* 0.9 units in both reaction series considered when passing from water to aqueous 2.25 M Bu$_4$NBr and 80% (v/v) DMSO whose electrophilic solvating power is reduced compared with pure water. The susceptibility of the *ortho* inductive effect to temperature variation in alkaline hydrolysis of substituted phenyl benzoates in pure water $c_{5(ortho)}$ is equal to 0.68×10^3 and $b_{I(ortho)} = 0.76 \times 10^3$ (Tables S2 and S4). The corresponding values of $c_{5(ortho)}$ and $b_{I(ortho)}$ for alkaline hydrolysis of substituted phenyl tosylates are 1.54×10^3 and 1.55×10^3, respectively (Table S3 and S5). The $c_{5(ortho)}$ and $b_{I(ortho)}$ values grow by *ca* 0.4 units in both reaction series considered when passing from pure water to aqueous 2.25 M Bu$_4$NBr and 80% (v/v) DMSO. The variation of

Table 3. The variation of the β (K) values calculated with Eqns (23) and (28) with solvent for alkaline hydrolysis of substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates[a]

Reaction constant	Equation used	Water $\Delta E_S = 0$[a]	5.3 M NaClO$_4$ $\Delta E_S = 3.79$[a]	0.5 M Bu$_4$NBr $\Delta E_S = -4.91$[a]	2.25 M Bu$_4$NBr $\Delta E_S = -13.63$[a]	80% (v/v) DMSO $\Delta E_S = -13.81$[a]
		Meta- and *para*-substituted phenyl benzoates				
$\beta = c_{3(m,p)}/c_{1(m,p)}$	Equation (23)	∞	∞	1426	649	625
$\beta = b_{m,p}/a_{m,p}$	Equation (26)	∞	∞	872	648	604
		Ortho-substituted phenyl benzoates				
$\beta = c_{5(ortho)}/c_{1(ortho)}$	Equation (24)	969	1282	875	657	726
$\beta = b_{I(ortho)}/a_{I(ortho)}$	Equation (27)	788	975	779	734	711
		Meta- and *para*-substituted phenyl tosylates				
$\beta = c_{3(m,p)}/c_{1(m,p)}$	Equation (23)	∞	∞	1291	804	704
$\beta = b_{m,p}/a_{m,p}$	Equation (26)	∞	∞	1147	841	719
		Ortho-substituted phenyl tosylates				
$\beta = c_{5(ortho)}/c_{1(ortho)}$	Equation (24)	900	960	854	783	753
$\beta = b_{I(ortho)}/a_{I(ortho)}$	Equation (27)	886	1298	960	764	780
		Alkyl benzoates				
$\beta = c_{4(Alk)}/c_{1(Alk)}$	Equation (25)	∞	∞	2197	1457	1378
$\beta = b_{I(Alk)}/a_{I(Alk)}$	Equation (28)	∞	∞	2352	1309	1242

[a] By ΔE_S the values of the solvent electrophilicity parameters are shown.

the temperature-dependent *ortho* inductive effect with solvent is nearly twice less compared with the *meta* and *para* polar effect, though in water the susceptibility of the *ortho* inductive effect to temperature variation surpasses that of the *meta* and *para* polar effect in both reaction series considered *ca* twice:

$$\frac{c_{5(ortho)Benz}}{c_{3(m,p)Benz}} = \frac{c_{5(ortho)Tos}}{c_{3(m,p)Tos}} = \frac{b_{I(ortho)Benz}}{b_{I(m,p)Benz}} = \frac{b_{I(ortho)Tos}}{b_{(m,p)Tos}} \approx 2$$

When passing from pure water to aqueous 2.25 M Bu_4NBr and 80% (v/v) DMSO, the susceptibility of the alkyl polar substituent effect to temperature variation grows nearly by the same extent as it was observed for the *meta* and *para* polar effect. In alkaline hydrolysis of substituted alkyl benzoates, $C_6H_5CO_2R$, in pure water $c_{4(Alk)} = 1.09 \times 10^3$ and $c_{4(Alk)} = 1.82 \times 10^3$ in aqueous 80% (v/v) DMSO (Eqn (12), Table S2).

The reaction constant $c_{1(m,p)}$ in Eqn (10) and $a_{(m,p)}$ in Eqn (13), characterizing the temperature-independent *meta*, *para* polar effect, or the *meta*, *para* polar effect dependent entropy term, equal to zero both in the alkaline hydrolysis of substituted phenyl benzoates and tosylates in water, which corresponds to the isoentropic reaction series. The change in the reaction constants $c_{1(m,p)}$ and $a_{(m,p)}$ value in the transition from water to aqueous 2.25 M Bu_4NBr and 80% (v/v) DMSO is about 1.9 units both in the alkaline hydrolysis of benzoates and tosylates (Tables S2–S5). In the case of *meta* and *para* substituents when passing from water to aqueous 2.25 M Bu_4NBr and 80% (v/v) DMSO both reaction series considered changed from isoentropic to isokinetic reaction series. The reaction constants $c_{1(ortho)}$ in Eqn (11) and $a_{(ortho)}$ in Eqn (14), characterizing the susceptibility of the entropy term to *ortho* inductive effect, are different from zero in all solvents considered. In transition from water to aqueous 2.25 M Bu_4NBr and 80% (v/v) DMSO the reaction constants $c_{1(ortho)}$ and $a_{(ortho)}$ diminish twice less than the same constants $c_{1(m,p)}$ and $a_{(m,p)}$ for *meta* and *para* polar effect.

To study the influence of the solvent electrophilicity, E_S, on the susceptibilities of the polar substituent effects to temperature variation, the values of the reaction constants $c_{3(m,p)}$, $c_{5(ortho)}$, $c_{4(Alk)}$, and $b_{(m,p)}$, $b_{I(ortho)}$, and $b_{I(Alk)}$ for water, aqueous 5.3 M $NaClO_4$, 0.5 M Bu_4NBr, 2.25 M Bu_4NBr, and 80% (v/v) DMSO were subjected to linear regression analysis according to Eqns (16) and (17), respectively. The temperature-dependent polar substituent effect (*i.e.* the polar substituent effect on activation energies) in alkaline hydrolysis of substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates appeared to be nicely correlated with the solvent electrophilicity parameter, ΔE_S (Fig. 1, Fig. S1, Table 2), similar as it was found earlier[1–3] for the polar substituent effects at the constant temperature. The m_1 values in Eqns (16) and (17) and c_3 in Eqn (20), characterizing the variation of the temperature-dependent polar substituent effects with the
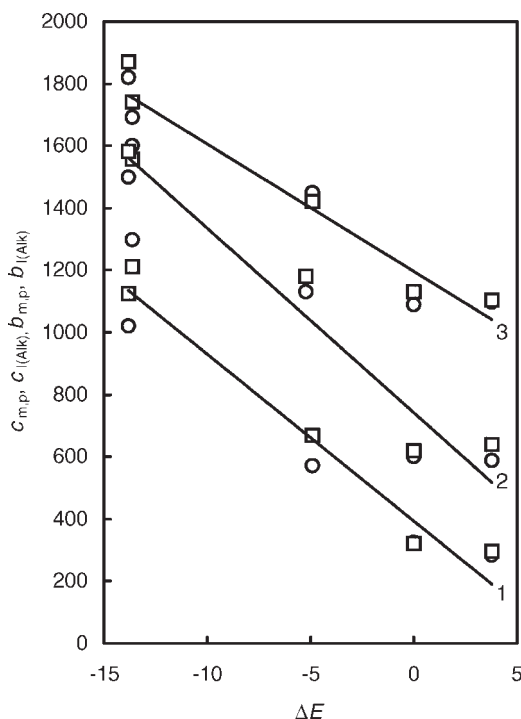

Figure 1. Dependence of the temperature-dependent *meta*, *para*, and alkyl polar effect on the solvent electrophilicity, ΔE_S, for alkaline hydrolysis of substituted phenyl benzoates (plot 1), phenyl tosylates (plot 2), and alkyl benzoates (plot 3). The values of $c_{3(m,p)}$, $c_{4(Alk)}$ (○) and $b_{m,p}$, and $b_{I(Alk)}$ (□) for water, aqueous 5.3 M $NaClO_4$, 0.5 M Bu_4NBr, 80% (v/v) DMSO, and 2.25 M Bu_4NBr were used (Tables S2–S5)

solvent electrophilicity, ΔE_S, were found to be nearly the same when calculated with Eqns (16) and (17) or with Eqn (20) (Eqns (29) and (33), Table 2).

In case the variation of the temperature-dependent substituent polar effects with the solvent electrophilicity parameters, ΔE_S, was studied with Eqn (20), including the ρ values in various solvents and at various temperatures (Table S6), we obtained:

$$\rho^{\circ}_{(m,p)Benz} = (0.341 \pm 0.010)\left(\frac{10^3}{T}\right)$$
$$+ (0.090 \pm 0.053)\Delta E_S$$
$$- (46.4 \pm 16.1)\left(\frac{1}{T}\right)\Delta E_S \quad (29)$$
$$s_0 = 0.231, \frac{n}{n_0} = \frac{23}{23}$$

$$\rho^{\circ}_{(m,p)Tos} = (0.651 \pm 0.016)\left(\frac{10^3}{T}\right)$$
$$+ (0.106 \pm 0.076)\Delta E_S$$
$$- (54.9 \pm 25.0)\left(\frac{1}{T}\right)\Delta E_S \quad (30)$$
$$s_0 = 0.370, \frac{n}{n_0} = \frac{21}{21}$$

$$\rho_{I(ortho)Benz} = -(0.898 \pm 0.781)$$
$$+ (0.74 \pm 0.13)\left(\frac{10^3}{T}\right)$$
$$+ (0.0568 \pm 0.0522)\Delta E_S \quad (31)$$
$$- (28.4 \pm 16.0)\left(\frac{1}{T}\right)\Delta E_S$$
$$s_0 = 0.258, \frac{n}{n_0} = \frac{24}{24}$$

$$\rho_{I(ortho)Tos} = -(1.543 \pm 0.736)$$
$$+ (1.48 \pm 0.14)\left(\frac{10^3}{T}\right)$$
$$+ (0.0501 \pm 0.0495)\Delta E_S \quad (32)$$
$$- (25.8 \pm 16.2)\left(\frac{1}{T}\right)\Delta E_S$$
$$s_0 = 0.247, \frac{n}{n_{00}} = \frac{21}{21}$$

$$\rho_{I(Alk)Benz} = (1.136 \pm 0.011)\left(\frac{10^3}{T}\right)$$
$$+ (0.113 \pm 0.071)\Delta E_S$$
$$- (51.6 \pm 21.6)\left(\frac{1}{T}\right)\Delta E_S \quad (33)$$
$$s_0 = 0.247, \frac{n}{n_0} = \frac{21}{21}$$

In the alkaline hydrolysis of substituted phenyl benzoates the *ortho*, *meta*, and *para* temperature-dependent polar effects vary with the solvent electrophilicity *ca* to the same extent as in the alkaline hydrolysis of substituted phenyl tosylates, although the ratio of the susceptibilities to polar effect of substituents in water differs twofold: $\rho^\circ_{(m,p)Tos}/\rho^\circ_{(m,p)Benz} = \rho_{I(ortho)Tos}/\rho_{I(ortho)Benz} \approx 2$. In the case of *meta* and *para* substituents the variation of the temperature-dependent polar effect with the solvent electrophilicity was *ca* twice higher than that for the *ortho* inductive effect. The corresponding values for reaction constants $m_{1(m,p)}$ in Eqns (16) and (17) and $c_{3(m,p)}$ in Eqn (20) (Eqns (29) and (30)) were in the range from -46 to -54 in alkaline hydrolysis of substituted phenyl benzoates and in the range from -55 to -59 for the alkaline hydrolysis substituted phenyl tosylates. In the case of *ortho* substituents, the susceptibility of the temperature-dependent inductive effect to variation of the solvent electrophilicity $m_{1(ortho)}$ and $c_{3(ortho)}$ ranges from -25 to -32 in both the alkaline hydrolysis of *ortho*-substituted phenyl benzoates and phenyl tosylates. In alkaline hydrolysis of alkyl benzoates the variation of the temperature-dependent polar effect with the solvent electrophilicity was nearly the same as in the case of *meta*- and *para*-substituted phenyl benzoates (the value of $m_{1(Alk)}$ and $c_{3(Alk)}$ ranges from -44 to -52, Table 2).

The values of m_0 in Eqns (16) and (17) and c_1 in Eqn (20) are the susceptibilities of the polar substituent effect to temperature variation for water considered as standard medium (Eqns (29) and (33), Tables 2, S2–S5). The c_2 constant in Eqn (20) characterizes the variation of the temperature-dependent substituent effects at $1/T = 0$, with the solvent electrophilicity, E_S. The value of c_0 in Eqn (20) was considered different from zero for *ortho* derivatives, as the inductive effect in the alkaline hydrolysis in water was found isokinetic one. $c_2 = c_0$ for the standard medium (pure water) where $\Delta E_S = 0$. The values of c_2 in Eqn (20) and p_1 in Eqns (18) and (19), characterizing the variation of the temperature-independent polar substituent effect with the solvent electrophilicity, ΔE_S, were found to be nearly the same when calculated with Eqns (18) and (19) or with Eqn (20) (Table 2). The values of c_2 and p_1 in the case of *meta*, *para* polar effect, and *ortho* inductive effect in both reaction series considered were in the ranges 0.090–0.128 and 0.0454–0.066, respectively.

We found the dependences of the $\rho^\circ_{m,p}$, $\rho_{I(ortho)}$, and $\rho_{I(Alk)}$ values on the $(1/T)$ term for water, 2.25 M aqueous 5.3 M NaClO$_4$, 0.5 M Bu$_4$NBr, and 80% (v/v) DMSO to cross nearly at the same temperature $(1/T \approx 2 \times 10^{-3})$ in alkaline hydrolysis of substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates (Fig. 2 and Fig. S2). At the isosolvent effect temperature $(\beta_{isosolv} \approx 500\,K)$ the susceptibilities to *ortho, meta*, and *para* substituent effects, that is, the ρ values for a reaction considered in all solvents studied are equal to each other. The values of ρ_{iso} are: $\rho_{iso} \approx 0.7$ for the alkaline hydrolysis of phenyl
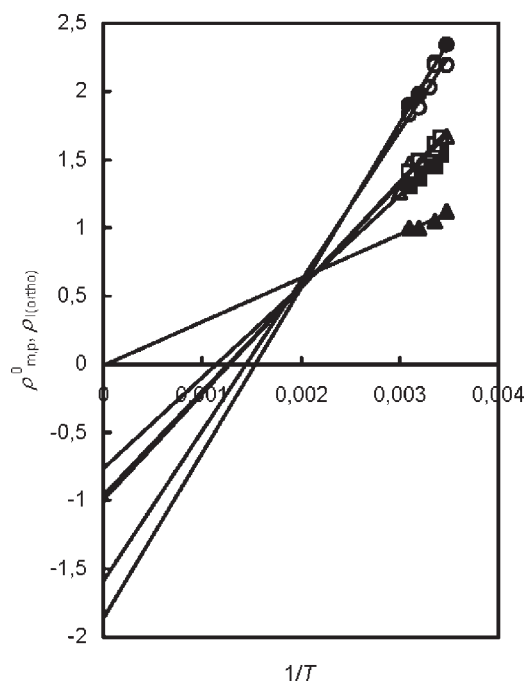

Figure 2. Dependence of $\rho^\circ_{m,p}$ (▲, ■, ●) and $\rho_{I(ortho)}$ (△, □, ○) on (1/T) for alkaline hydrolysis of substituted phenyl benzoates in water, 0.5 M Bu$_4$NBr, and 2.25 M Bu$_4$NBr (Table S6)

benzoates, $\rho_{\text{iso}} \approx 1.3$ for phenyl tosylates, and $\rho_{\text{iso}} \approx 2.0$ for alkyl benzoates. The values of $\rho_{\text{I(ortho)}}$ and $\rho^{\circ}_{\text{(m,p)}}$ for all media studied cross at the same isosolvent effective temperature $\beta_{\text{isosolv}} \approx 500\,\text{K}$ at which $\rho_{\text{I(ortho)}} = \rho^{\circ}_{\text{(m,p)}}$ and the additional inductive effect from the *ortho* position (compared with *para* derivatives) disappears for all solvents studied. Earlier,[2,4,15] we found the additional *ortho* inductive effect to disappear at $T \approx 500\,\text{K}$ in the alkaline hydrolysis of substituted phenyl benzoates and tosylates in water and for phenyl tosylates in aqueous $0.5\,\text{M}\ \text{Bu}_4\text{NBr}$.

We calculated the value of the isosolvent temperature β_{isosolv} separately for *meta* and *para* polar (inductive), *ortho* inductive, and alkyl inductive effects with Eqn (21) ($\beta_{\text{isosolv}} = -c_3/c_2$) using reaction constants from Eqn (20) and from the relation of the sensitivities of the temperature-dependent and the temperature-independent terms to the solvent electrophilicity, E_S ($\beta_{\text{isosolv}} = -m_1/p_1$, Eqn (22)). The values of $1/\beta_{\text{isosolv}}$ calculated with $1/\beta_{\text{isosolv}} = -c_2/c_3$ (Eqn (20)) change in a quite narrow limits, from 1.93×10^{-3} to 2.19×10^{-3} (Table 2). We found the isosolvent temperatures to be the same when the *meta* and *para* polar, *ortho* inductive, and alkyl inductive effects were considered both in the alkaline hydrolysis benzoates, phenyl tosylates:

$$\beta_{\text{isosolv}} = \left[\left(\frac{-c_3}{c_2}\right)_{\text{m,p}} = \left(\frac{-c_3}{c_2}\right)_{\text{I(ortho)}} = \left(\frac{-c_3}{c_2}\right)_{\text{I(Alk)}} \right]_{\text{Benz}}$$

$$= \left[\left(\frac{-c_3}{c_2}\right)_{\text{m,p}} = \left(\frac{-c_3}{c_2}\right)_{\text{I(ortho)}} \right]_{\text{Tos}} =$$

$$= \left[\left(\frac{-m_1}{p_1}\right)_{\text{m,p}} = \left(\frac{-m_1}{p_1}\right)_{\text{I(ortho)}} = \left(\frac{-m_1}{p_1}\right)_{\text{I(Alk)}} \right]_{\text{Benz}}$$

$$= \left[\left(\frac{-m_1}{p_1}\right)_{\text{m,p}} = \left(\frac{-m_1}{p_1}\right)_{\text{I(ortho)}} \right]_{\text{Tos}} = 500\,\text{K}$$

At the isosolvent effect temperature, β_{isosolv}, the substituent effects in all media considered become equal to ρ_{iso} which corresponds to the ρ value of the corresponding reaction series in water at $\beta_{\text{isosolv}} = 500\,\text{K}$. K. At isosolvent temperature, β_{isosolv}, the substituent polar effects considered in all media turn to zero if the substituent effects relative to standard solution (water) were considered. The variation of the temperature-dependent term (enthalpy term) ($c_S - c_{\text{water}}$, $c = c_{3(\text{m,p})}$, $c_{5(\text{ortho})}$, $c_{4(\text{Alk})}$ in Eqns (10) and (12), Tables S2, S3) with the temperature-independent term (entropy term) ($c_{1(S)} - c_{1(\text{water})}$, $c = c_{1(\text{m,p})}$, $c_{1(\text{ortho})}$, $c_{1(\text{Alk})}$ in Eqns (10) and (12), Tables S2, S3) on going from water to a medium considered is shown in Fig. 3. The relationship between the substituent-dependent enthalpy and entropy terms has the slope $-\beta_{\text{isosolv}} \approx 500\,\text{K}$ and includes on the same plot the points for the alkaline hydrolysis of substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates when the *meta* and *para* polar, *ortho* inductive, and alkyl inductive effects were considered. The value of the isosolvent effect
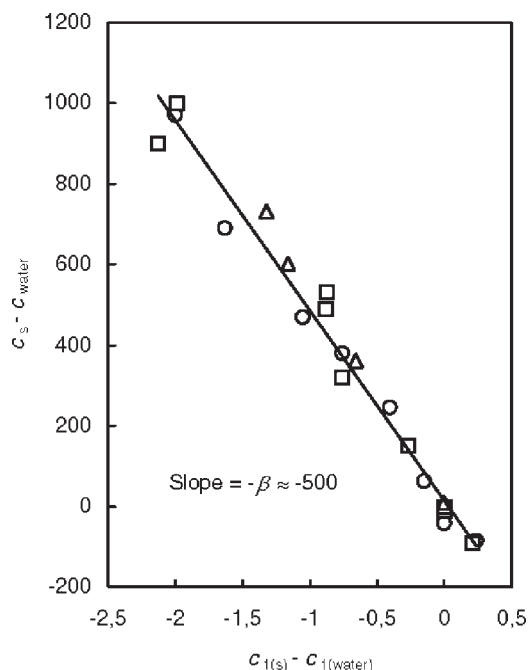

Figure 3. The variation of the enthalpy term ($c_S - c_{\text{Water}}$) ($c = c_{3(\text{m,p})}$, $c_{5(\text{ortho})}$, $c_{4(\text{Alk})}$ in Eqns (4)–(6), Tables 3 and 4) with the entropy term $c_{1(S)} - c_{1(\text{Water})}$ ($c = c_{1(\text{m,p})}$, $c_{1(\text{ortho})}$, $c_{1(\text{Alk})}$ in Eqns (10)–(12), Tables S2–S3) on going from water to a medium considered for alkaline hydrolysis of substituted phenyl benzoates ($\bigcirc$), phenyl tosylates ($\square$), and alkyl benzoates ($\triangle$)

temperature $\beta_{\text{isosolv}} = 500\,\text{K}$ ($1/\beta_{\text{isosolv}} = 2 \times 10^{-3}$) was found to be the common characteristic for the all polar substituent effects in the alkaline hydrolysis of substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates in all media considered. The common β_{isosolv} values demonstrate that the *meta*, *para* polar, *ortho*, and alkyl inductive effects in the alkaline hydrolysis of benzoates and tosylates reaction series vary with temperature and solvent electrophilicity all by the same extent when to consider substituent effects relative to the corresponding substituent effects in water. At the isosolvent temperature the substituent effects in various media are equal to each other and are independent of media.

At the isokinetic temperature β for a medium considered all the reactions in the series have the same rate constant (substituent effect equals to zero). We found the isokinetic temperature β to be dependent on the electrophilic solvating power of media considered (Table 3). The isokinetic temperature β in the case of *ortho* and *alkyl* derivatives diminishes less as compared with the *meta* and *para* derivatives on going from water to solvent whose electrophilic solvating power is reduced compared with pure water (Table 3). In water the alkaline hydrolysis of *meta*- and *para*-substituted phenyl benzoates and tosylates as well as alkyl benzoates was found to be isoentropic ($\beta = \infty$), in less electrophilic media isokinetic ($\beta > 0$), and in media with very strong electrophilic solvating power these reaction series should turn to isoenthalpic. Similarly, the alkaline hydrolysis of

meta and *para* benzoates should become isoenthalpic ($\beta = 0$, Eqn (29)) in medium with $\Delta E_S = 7.4$. The inductive term in alkaline hydrolysis of *ortho*-substituted phenyl benzoates and tosylates relative to the temperature variation was isokinetic and varied with temperature and solvent nearly twice less than the polar effect of *meta* and *para* derivatives.

The common $\beta_{isosolv}$ value for both the alkaline hydrolysis of benzoates and tosylates shows that the substituent effects are similarly dependent on both temperature and solvent in both reaction series considered. Therefore, quite similar reaction mechanisms are required for two reaction series studied. The alkaline hydrolysis of aryl benzoates is regarded as following the addition–elimination mechanism via tetrahedral intermediate path.[50,51] Most authors support the stepwise $B_{Ac}2$ mechanism, while the formation of the tetrahedral intermediate $R_1CO^-(OH)OR_2]$ by addition of the hydroxide ion to carbonyl atom of ester is considered to be rate-determining step.[50–55] Similarly, the alkaline hydrolysis of substituted phenyl tosylates occurs with the S_N2 mechanism of the nucleophilic substitution, when the hydroxide ion attacks sulfonyl sulfur center by formation of the negatively charged transition state $[4\text{-}CH_3C_6H_4S(O)_2^-(OH)OAr]$.[56–58] In both the alkaline hydrolysis of benzoates and tosylates we obtained good correlations with σ° constants (not with σ^-) that proves that the reactions studied occur by a stepwise mechanism[52,59–61] not a concerted pathway[62–63] and the formation of the intermediate is the rate-determining step. The transition states in both reaction studied are characterized by the well advanced C—OH or S—OH bond formation but negligible C—OAr and S—OAr bond breakage. In all solvents used and at all temperatures in both reaction series considered the electron-withdrawing substituents enhance the reactivity and decrease the activation energy. This could be attributed to destabilization of the resonance forms in the esters ground state[59,64] and delocalization of the negative charge in the transition state with the electron-withdrawing substituents. The electron-donating substituents show the opposite effect. Compared to unsubstituted derivative, the compounds with electron-donating substituents showed the lowered reactivity and the higher activation energy as in the case of the electron-donating substituents the ground state of esters is more stabilized by resonance forms and the activated complex is destabilized by localization of the negative charge.

It follows from Eqns (29) and (33) that the *meta* and *para* polar and alkyl inductive effects in both the alkaline hydrolysis of substituted phenyl benzoates and tosylates are varying simultaneously with temperature and the solvent electrophilicity, E_S, as expressed by Eqns (34) and (35):

$$(\rho_{m,p})_S - (\rho_{m,p})_{Water} = 0.10\Delta E_S - 50\left(\frac{1}{T}\right)\Delta E_S \quad (34)$$

For the *ortho* inductive effect we obtained Eqn (35) (see Eqns (32) and (33)):

$$(\rho_{I-ortho})_S - (\rho_{I-ortho})_{Water}$$
$$= 0.05\Delta E_S - 25\left(\frac{1}{T}\right)\Delta E_S \quad (35)$$

From Eqns (34) and (35) it follows that in all media considered the temperature-dependent or enthalpy term and the temperature-independent or entropy term show the opposite influence on the substituent effects and the reaction rates while the changes in activation energies, ΔE, and $\Delta \log A$ caused by a substituents are in the same direction. In solvents whose electrophilic solvating power is reduced compared to water ($\Delta E_S < 0$) the changes in both the activation energy ($E_X - E_H$) and the ($\log A_X - \log A_H$) value due to substituent effects as compared to the same values in water in the case of the electron-withdrawing substituents are lower, but higher for electron-donating substituents. In media with lower electrophilic solvating power compared to water ($\Delta E_S < 0$) the electrophilic solvatation of the transition state is favored by electron-donating substituents which raises the ester reactivity, while the activation energy becomes higher. In media with $\Delta E_S < 0$, the electron-withdrawing substituents lower both the activation energy and the electrophilic solvatation of the transition state (by hydrogen-bond donating water molecules) as the electron-withdrawing substituents delocalize to the negative charge of the transition state. This is in accord with assumption made by Buncel[53] that in the esters' hydrolysis the transition state structure changes with changing the solvent composition. The negative charge of the transition state in the esters hydrolysis is considered[13] to increase when going to the less electrophilic media compared to water (aqueous Bu_4NBr and 80% DMSO solutions) and decrease (compared to water) in aqueous 5.3 M $NaClO_4$ whose electrophilic solvating power is enhanced compared to water. In aqueous 5.3 M $NaClO_4$ solution the transition state should become less negative due to complexation of Na^+ and H-bonding-water molecules to negatively charged transition state[65] due to the increased H-bond donating capability of water in inorganic salt solutions.[66] Besides discussing the importance of the influence of the variation of the hydrogen-bonding donor-assisted electrophilic solvation of the transition state of the alkaline ester hydrolysis one should not forget about the similar effect on the change of the nucleophilic reactivity of hydrogen-bonded OH^- ion in aqueous solution of different H-bond donating power. The stronger the dispersal of the negative charge of OH^- ion due to H-bond by water molecules, while going to more electrophilic media, the lower (at a fixed substituent) the rate constants k (see Table 1) (or the higher the activation energies). In solution with the stronger electrophilic power ($\Delta E_S > 0$) the electron-withdrawing substituents increase the activation energy as compared to water, as

electron-withdrawing substituents delocalizing of the charge in the transition state do not favor the complexation of Na^+ or water molecules by H-bond to negatively charged transition state. In media $\Delta E_S > 0$, the electron-withdrawing substituents favor and electron-donating substituents disfavor the reactivity caused by solvatation (Eqns (34) and (35)).

The difference $(\rho)_S - (\rho)_{Water}$ reaches zero and changes its sign at $T = \beta_{isosolv} = 500$ K. When going from water to solution whose electrophilicity power is lower compared to water $(\Delta E_S < 0)$: $(\rho)_S - (\rho)_{Water} > 0$ at $(1/T) > 1/\beta_{isosolv}$, and $(\rho)_S - (\rho)_{Water} < 0$ at $(1/T) < 1/\beta_{isosolv}$. In media with strong electrophilicity power $(\Delta E_S > 0)$: $(\rho)_S - (\rho)_{Water} < 0$ at $(1/T) > 1/\beta_{isosolv}$, and $(\rho)_S - (\rho)_{Water} > 0$ at $(1/T) < 1/\beta_{isosolv}$.

The dependence of the *ortho* inductive effect on both temperature and solvent (Eqn (47)) and the isosolvent temperature ($\beta_{isosolv} = 500$ K common with *meta* and *para* polar effect) let us consider that the different from *para* and *meta* derivatives behavior of the *ortho* inductive effect relative to temperature and solvent variation is produced by steric inhibition to solvatation.[67] The *ortho* substituents near the reaction center could hinder solvatation of the reaction center in transition state more than in the initial state.

CONCLUSIONS

The susceptibility to temperature variation of the *meta* and *para* polar substituent effect and the *ortho* inductive effect in the alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4$—X, and phenyl tosylates, $4\text{-}CH_3$—$C_6H_4SO_2OC_6H_4$—X, and the alkyl polar effect in alkyl benzoates, $C_6H_5CO_2R$, in water, aqueous 5.3 M $NaClO_4$, 0.5 M Bu_4NBr, 2.25 M Bu_4NBr, and 80% (v/v) DMSO was determined. Both the temperature-dependent (i.e., polar substituent effect on activation energies) and the temperature-independent polar substituent effects (i.e., the polar substituent effect on the log$A$ values) in alkaline hydrolysis of substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates were found to be nicely correlated with the solvent electrophilicity parameter, ΔE_S, which characterizes the H-bond donating power of the solvent and significantly influences the solvation of the transition state, as well as the OH^- anion. The substituent effects were found to vary with temperature and the solvent electrophilicity, E_S, compared to water by the same extent in alkaline hydrolysis of substituted phenyl benzoates and tosylates: $(\rho_{m,p})_S - (\rho_{m,p})_{Water} = 0.10\Delta E_S - 50(1/T)\Delta E_S$, $(\rho_{I-ortho})_S - (\rho_{I-ortho})_{Water} = 0.05\Delta E_S - 25(1/T)\Delta E_S$. In both reaction series considered in the case of *meta* and *para* polar substituent effect the dependence on both temperature and solvent electrophilicity, ΔE_S, was *ca* twice higher than that for the *ortho* inductive effect. In alkaline hydrolysis of alkyl benzoates the variation of the polar substituent effects

with temperature and solvent electrophilicity was nearly by the same extent as in the case of *meta* and *para* polar effect. The $\rho^\circ_{(m,p)}$, $\rho_{I(ortho)}$, and $\rho_{I(Alk)}$ values dependent on the $(1/T)$ term for various solvents were found to cross nearly at the same isosolvent temperature $(1/\beta_{isosolv} \approx 2 \times 10^{-3})$ for *meta, para, ortho*, and alkyl substituents in alkaline hydrolysis of substituted phenyl benzoates, phenyl tosylates, and alkyl benzoates. At isosolvent temperature the differences $(\rho)_S - (\rho)_{Water}$ become zero for all polar substituents effects in all media considered. At $\beta_{isosolv} \approx 500$ K, $\rho_{I(ortho)} = \rho^\circ_{(m,p)}$ and the additional inductive effect from the *ortho* position (compared with *para* derivatives) disappears for all solvents studied. The isokinetic temperature for a medium considered, β, was found to diminish with going from water to solvent whose solvent electrophilicity is reduced as compared with water.

SUPPLEMENTARY MATERIAL

The following tables and figures are available as supplementary material in Wiley Interscience:

Table S1: The values of log$A$ and activation energy, E (kJ mol^{-1}), for the alkaline hydrolysis of substituted alkyl benzoates, $C_6H_5CO_2R$, in aqueous 0.5 M Bu_4NBr and 5.3 M $NaClO_4$; Table S2: results of the correlation with Eqns (10) and (12) for the alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4$—X, and alkyl benzoates $C_6H_5CO_2R$, in water, aqueous 5.3 M $NaClO_4$, 0.5 M Bu_4NBr, 2.25 M Bu_4NBr, and 80% (v/v) DMSO; Table S3. Results of the correlation with Eqns (10) and (11) for the alkaline hydrolysis of phenyl tosylates, $4\text{-}CH_3$—$C_6H_4SO_2OC_6H_4$—X, in water, aqueous 5.3 M $NaClO_4$, 0.5 M Bu_4NBr, 2.25 M Bu_4NBr, and 80% (v/v) DMSO; Table S4: results of the correlation with $\rho_{TS} = a + b(1/T)$ (Eqns (13) and (15)) for the alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4$—X, and alkyl benzoates, $C_6H_5CO_2R$, in water, aqueous 5.3 M $NaClO_4$, 0.5 M Bu_4NBr, 2.25 M Bu_4NBr, and 80% (v/v) DMSO; Table S5: results of the correlation with $\rho_{TS} = a + b(1/T)$ (Eqns (13) and (14)) for the alkaline hydrolysis of substituted phenyl tosylates, $4\text{-}CH_3$—$C_6H_4SO_2OC_6H_4$—X, in water, aqueous 5.3 M $NaClO_4$, 0.5 M Bu_4NBr, 2.25 M Bu_4NBr, and 80% (v/v) DMSO; Table S6: the values of $\rho^\circ_{(m,p)}$, $\rho_{I(ortho)}$, and $\rho_{I(Alk)}$ for alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4$—X, phenyl tosylates, $4\text{-}CH_3$—$C_6H_4SO_2OC_6H_4$—X, and alkyl benzoates, $C_6H_5CO_2R$, in water, aqueous 5.3 M $NaClO_4$, 0.5 M Bu_4NBr, 2.25 M Bu_4NBr, and 80% (v/v) DMSO; Figure S1: Dependence of the temperature-dependent *ortho* inductive effect on the solvent electrophilicity, ΔE_S, for alkaline hydrolysis of substituted phenyl benzoates (plot 1) and phenyl tosylates (plot 2). The values of $c_{5(ortho)}$ ($\bigcirc$) and $b_{I(ortho)}$ ($\square$) for water, aqueous 5.3 M $NaClO_4$, 0.5 M Bu_4NBr, 80% (v/v) DMSO, and 2.25 M Bu_4NBr were used

(Tables S2–S5); Figure S2: Dependence of $\rho_{I(Alk)}$ on $(1/T)$ for alkaline hydrolysis of alkyl-substituted benzoates in aqueous 5.3 M NaClO$_4$ (plot 1), water (plot 2), aqueous 0.5 M Bu$_4$NBr (plot 3), 80% (v/v) DMSO (plot 4), and 2.25 M Bu$_4$NBr (plot 5) (Table S6).

Acknowledgements

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