Journal of the Serbian Chemical Society
JSCS@tmf.bg.ac.rs • www.shd.org.rs/JSCS

J. Serb. Chem. Soc. 74 (12) 1335–1357 (2009)
JSCS–3922

UDC 547–32:547.437'631:
544–145.55:541.42
Authors' Review

AUTHORS' REVIEW

The study of linear solvation energy relationship for the reactivity of carboxylic acids with diazodiphenylmethane in protic and aprotic solvents

GORDANA S. UŠĆUMLIĆ*# and JASMINA B. NIKOLIĆ#

Department of Organic Chemistry, Faculty of Technology and Metallurgy, University of Belgrade, Karnegijeva 4, P.O. Box 3505, 11120 Belgrade, Serbia

(Received 15 June 2009)

Abstract: Solvent effects on the reactivity of cycloalkenecarboxylic, cycloalkeneacetic, 2-substituted cyclohex-1-enecarboxylic, 2-substituted benzoic, 2-substituted cyclohex-1-eneacetic, 2-substituted phenylacetic, 2-phenylcyclohex-1-enecarboxylic, 2-phenylbenzoic and 2-phenylacrylic acids with diazodiphenylmethane (DDM) were investigated. In order to explain the kinetic results through solvent effects, the second-order rate constants for the reaction of the examined acids with DDM were correlated using the Kamlet–Taft solvatochromic equation. The correlations of the kinetic data were realized by means of multiple linear regression analysis and the solvent effects on the reaction rates were analyzed in terms of the contributions of the initial and the transition state. The signs of the equation coefficients support the proposed mechanism. Solvation models for all the investigated acids are suggested. The quantitative relationship between the molecular structure and the chemical reactivity is also discussed.

Keywords: carboxylic acids; linear solvation energy relationship; diazodiphenylmethane; aprotic solvents; protic solvents.

CONTENTS

---

* Corresponding author. E-mail: goca@tmf.bg.ac.rs
# Serbian Chemical Society member.

doi: 10.2298/JSC0912335U

1. INTRODUCTION

The effect of different solvents on the rates of chemical changes was one of the earliest kinetic problems to be studied.[1–3] The development of correlation analysis in the area of solvent effects has proved to be a slow and difficult process and only within the last 20 years has there been any considerable progress. Application of the techniques of multiple regression has proved to be strikingly successful and has greatly increased the understanding of the role of the solvent. Over the years, two main methods for the examination of the solvent effects on the reaction rates have been developed. First, the rate constants, either as log k or as $\Delta G^{\#}$ may be correlated with a physical parameter characteristic of the solvent, for example dielectric constant, solubility parameter, viscosity, *etc*., or with an empirical solvent parameter, such as Y, Z, *etc*.[4–6] This type of analysis has been extended to multiple linear correlations with a number of solvent parameters, notably by Shorter *et al*.[7] on the reaction of diazodiphenylmethane (DDM) and benzoic acid and more generally by Koppel and Palm[8] and by Kamlet and Taft and their co-workers.[9–11] In the second method, the solvent effect on log k or□□ $\Delta G^{\#}$ is dissected into contributions of the reactants (initial state) and the transition state, followed, where possible, by a comparison of solvent effects on the transition state with solvent effects on solutes that might function as suitable models for the transition state. This method has been applied not only to a number of standard organic reactions but also to organometallic and inorganic reactions.

Two groups of workers set out general equations for the correlations of solvent effects through multiple regression analysis. Koppel and Palm[8] used the four-parameter Eq. (1):

$$\log k = \log k_0 + gf(\varepsilon) + pf(n) + eE + bB \qquad (1)$$

in which $f(\varepsilon)$ is a dielectric constant function, usually $Q = (\varepsilon - 1)/(2\varepsilon + 1)$, $f(n)$ is a refractive index function, $(n^2 - 1)/(n^2 + 2)$, and E and B are measures of the electrophilic and nucleophilic solvation ability of the solvent, respectively. Koppel and Palm[8] and later Shorter *et al*.[7] quite successfully applied Eq. (1) to a variety of reaction types.

The Kamlet and Taft group of workers[11] used the alternative Eq. (2):

$$\log k = A_0 + s\pi^* + a\alpha + b\beta \qquad (2)$$

in which π^* is a measure of solvent dipolarity/polarizability, β represents the scale of the solvent hydrogen bond acceptor basicity, α represents the scale of the solvent hydrogen bond donor acidity and A_0 is the regression value of the solute property in the reference solvent, cyclohexane. The regression coefficients s, a and b measure the relative susceptibilities of the solvent-dependent solute property (log k or as $\Delta G^{\#}$) to the corresponding solvent parameters. Both Eq. (1) and Eq.(2) are general enough to be applied to almost any type of reaction. However, as will be shown, there are considerable advantages to be gained by the use of Eq. (2).[12]

This review demonstrates how the linear solvation energy relationship (LSER) method can be used to explain and present the multiple interacting effects of the solvent on the reactivity of carboxylic acids in their reaction with DDM. The solvent effects on the reaction rates were analyzed in terms of the contributions of the initial and the transition state. The quantitative relationship between the molecular structure and the chemical reactivity is discussed.

2. HYDROXYLIC SOLVENT EFFECTS ON THE KINETICS OF THE REACTION OF CARBOXYLIC ACIDS WITH DIAZODIPHENYLMETHANE

The reactivity of carboxylic acids with diazodiphenylmethane (DDM) is closely related to the molecular structure of the acid and the solvent present. The main advantage that makes this esterification convenient for examining the influence of the solvent and structure on the reactivity of the carboxylic acid is that a catalyst is not necessary for this reaction. It may vary in rate, but it occurs without any additional support and it follows second-order kinetics in protic and aprotic solvents.[13,14] The mechanism of this reaction has been thoroughly examined[15–17] and it was established that the rate-determining step involves a proton transfer from the carboxylic acid to DDM, whereby a diphenemethane-diazonium–carboxylate ion pair is formed, which rapidly reacts to give esters in the subsequent product-determining step (or ethers in the case of hydroxylic solvents):

$$Ph_2CN_2 + RCOOH \rightarrow Ph_2CHN_2^{+}\,{}^{-}O_2CR$$

In previous studies, the reactivity of 2-substitutedcyclohex-1-enecarboxylic acids,[18–20] 2-substitutedbenzoic acids,[13,14,18–20] 2-substitutedcyclohex-1-eneacetic acids,[21–23] 2-substitutedphenylacetic acids,[21–23] cycloalkanecarboxylic acids,[24–26] cycloalkenecarboxylic acids,[25,27,28] cycloalkeneacetic acids,[21,28,29] 2-(4-substitutedphenyl)cyclohex-1-enecarboxylic acids,[30–35] 2-(4-substituted phenyl)benzoic acids[35–38] and 2-(4-substitutedphenyl)acrylic acids[35,39,40] with DDM in various alcohols were investigated. The rate data for these acids were correlated with the simple and extended Hammett equations. The results showed that linear free energy relationships (LFER) are applicable to the kinetic data for the investigated acid systems. In recent papers,[23,25,28] hydroxylic solvent effects were examined on the reaction of the same carboxylic acids with DDM by means of the linear solvation energy relationship (LSER) concept, developed by Kamlet and Taft.[9]

The correlation equations obtained by stepwise regression for all the examined acids showed that the best approach, which helps the understanding of the hydroxylic solvent effects in the reaction, lies in the separate correlations of the kinetic data with the hydrogen bond donating (HBD) and hydrogen bond accepting (HBA) ability of a solvent (Eqs. (3a–3p)). The correlations are as follows:

Cyclopent-1-enecarboxylic acid:

$$\log k = -1.93 + (1.03 \pm 0.23)\pi^* + (1.43 \pm 0.53)\alpha \tag{3a}$$
$$R = 0.977,\ s = 0.08,\ n = 7;$$
$$\log k = -0.31 + (0.63 \pm 0.31)\pi^* - (1.06 \pm 0.36)\beta \tag{3b}$$
$$R = 0.981,\ s = 0.072,\ n = 7.$$

Cyclohex-1-enecarboxylic acid:

$$\log k = -1.92 + (1.05 \pm 0.23)\pi^* + (1.30 \pm 0.52)\alpha \tag{3c}$$
$$R = 0.977,\ s = 0.077,\ n = 7;$$
$$\log k = -0.06 + (0.79 \pm 0.38)\pi^* - (0.83 \pm 0.46)\beta \tag{3d}$$
$$R = 0.970,\ s = 0.089,\ n = 7.$$

Cyclohept-1-enecarboxylic acid:

$$\log k = -1.91 + (1.06 \pm 0.22)\pi^* + (1.16 \pm 0.51)\alpha \tag{3e}$$
$$R = 0.977,\ s = 0.070,\ n = 7;$$
$$\log k = -0.35 + (0.98 \pm 0.48)\pi^* - (0.66 \pm 0.44)\beta \tag{3f}$$
$$R = 0.960,\ s = 0.090,\ n = 7.$$

Cyclopent-1-eneacetic acid:

$$\log k = -3.56 + (0.80 \pm 0.33)\pi^* + (3.74 \pm 0.75)\alpha \tag{3g}$$
$$R = 0.980,\ s = 0.110,\ n = 7;$$
$$\log k = 1.91 - (2.47 \pm 0.31)\beta \tag{3h}$$
$$R = 0.963,\ s = 0.133,\ n = 7.$$

Cyclohex-1-eneacetic acid:

$$\log k = -3.33 + (0.75 \pm 0.41)\pi^* + (3.91 \pm 0.94)\alpha \tag{3i}$$
$$R = 0.960,\ s = 0.140,\ n = 7;$$
$$\log k = 1.66 - (2.26 \pm 0.36)\beta \tag{3j}$$
$$R = 0.940,\ s = 0.150,\ n = 7.$$

Cyclohept-1-eneacetic acid:

$$\log k = -3.12 + (0.67 \pm 0.42)\pi^* + (3.13 \pm 0.96)\alpha \tag{3k}$$
$$R = 0.950,\ s = 0.140,\ n = 7;$$
$$\log k = 1.44 - (2.06 \pm 0.35)\beta \tag{3l}$$
$$R = 0.930,\ s = 0.150,\ n = 7.$$

Benzoic acid:

$$\log k = -2.87 + (0.83 \pm 0.36)\pi^* + (3.02 \pm 0.73)\alpha \tag{3m}$$
$$R = 0.975,\ s = 0.103,\ n = 7;$$
$$\log k = 1.69 - (2.07 \pm 0.29)\beta \tag{3n}$$
$$R = 0.954,\ s = 0.124,\ n = 7.$$

Phenylacetic acid:

$$\log k = -2.48 + (0.85 \pm 0.31)\pi^* + (2.59 \pm 0.71)\alpha \qquad (3o)$$

$$R = 0.972,\ s = 0.105,\ n = 7;$$

$$\log k = 1.70 - (1.99 \pm 0.27)\beta \qquad (3p)$$

$$R = 0.950,\ s = 0.120,\ n = 7.$$

As the solvent effects on the examined reaction could not be clearly presented when all the solvent properties were taken together, an attempt was made to separate them into those that stabilize the transition state and those that influence the ground state before the reaction starts. Taking into consideration the reaction mechanism (Fig. 1), it can be noticed that, because of the charge separation in the transition state, a solvent of high polarity can stabilize this state, making the reaction faster; the electrophilic ability of a solvent can have a similar effect, affecting the carboxylic anion which also exists in the transition state. On the contrary, the nucleophilic solvating ability can be prominent in the ground state, stabilizing the carboxylic proton and, hence, retarding the reaction.

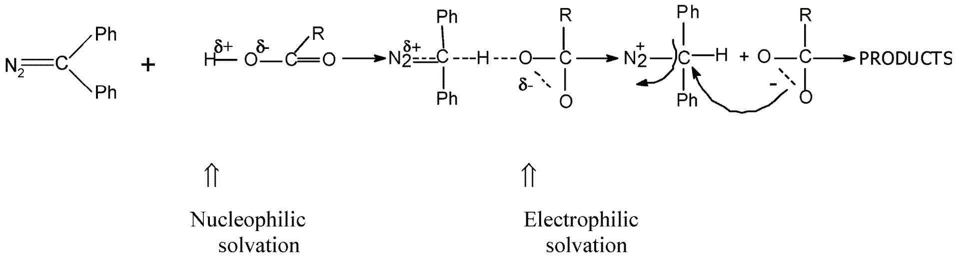


Fig. 1. The effects of the solvent on the mechanism of the reaction of carboxylic acids with DDM.

Multiple linear regression analysis (MLRA) is very useful in separating and quantifying such interactions on the examined reactivity. The first comprehensive application of multiple linear regression analysis to kinetic phenomena was that of Koppel and Palm[8] who listed regression constants for the simple Koppel–Palm equation for various processes. Aslan *et al.*[14] showed that correlation analysis of the second-order rate constants for the reaction of benzoic acid with DDM in hydroxylic solvents did not give satisfactory results with the Koppel–Palm mode.[8] They came to the conclusion that the possibility of Koppel–Palm analysis of data related to protic solvents depends on the fitting of the data in a regression with the main lines being determined by a much larger number of aprotic solvents.

These results point to a rather complex influence of hydroxylic solvents on the rate constants of the reaction between carboxylic acids and DDM. In these amphiprotic solvents, the complications can be caused by self-association type-AB hydrogen bonding, and multiple type-A and type-B interactions. In type-A hydrogen bonding, the solute acts as a HBA base and the solvent as a HBD acid. In type-B hydrogen bonding, the roles are reversed. Type-AB represents hydrogen bonding in which the solute acts as both a HBD acid and a HBA base, associating with at least two molecules of amphiprotic solvent in a probably cyclic complex. The obtained satisfactory results of the correlations of the kinetic data of examined acids by Kamlet–Taft equations with separate HBD and HBA abilities of the solvent, presented in this review, indicate that the selected model was correct. This means that this model gives a detailed interpretation of the solvating effects of the carboxylic group in different hydroxylic solvents. In these circumstances where both the solvent and solute are hydrogen bond donors, it has been proven to be quite difficult to untangle solvent dipolarity/polarizability, type-B hydrogen bonding and variable self-association effects from the usual multiple type-A hydrogen bonding interactions.

3. THE KAMLET–TAFT METHOD FOR THE EXAMINATION OF SOLVENT EFFECTS ON THE REACTIVITY OF CARBOXYLIC ACIDS WITH DIAZODIPHENYLMETHANE

Kamlet *et al.*[9] established that the effect of a solvent on the reaction rate should be given in terms of the following properties: *i*) the behavior of the solvent as a dielectric, facilitating the separation of opposite charges in the transition state, *ii*) the ability of the solvent to donate a proton in a solvent-to-solute hydrogen bond and thus stabilize the carboxylate anion in the transition state and *iii*) the ability of the solvent to donate an electron pair and therefore stabilize the initial carboxylic acid, by way of a hydrogen bond between the carboxylic proton and the solvent electron pair. The parameter π^* is an appropriate measure of the first property, while the second and the third properties are governed by the effects of the solvent acidity and basicity, quantitatively expressed by the parameters α and β, respectively. The solvent parameters (π^*, α and β) for hydrogen bond donor and non-hydrogen bond donor solvents (Eq. (2)) taken from the literature[11] are given in Table I. The linear dependence (LSER) on the solvent parameters were used to correlate and predict a wide variety of solvent effects, as well as to provide an analysis in the terms of knowledge and the theoretical concepts of molecular structural effects.[9]

To the best of our knowledge, the influence of aprotic solvents on the reactivity of carboxylic acids with DDM using the Kamlet–Taft treatment has not hitherto been systematically presented, except for benzoic acid.[9]

In recent papers,[41–44] the effects of a set of 12 aprotic and 3 protic solvents on the reaction of various carboxylic acids with DDM was examined by means of the linear solvation energy relationship (LSER) concept developed by Kamlet and Taft[9] (Eq. (2)). The correlation equations obtained by stepwise regression for all the examined acids showed that the total solvatochromic equation can be used in its complete form, without the separation of effects supporting the transition state (solvent polarity and hydrogen bond donating ability) and the ground state (hydrogen bond accepting ability).

TABLE I. Solvent parameters[11]

Solvent	π^*	α	β
Methyl acetate	0.60	0.00	0.42
Cyclohexanone	0.76	0.00	0.53
Diethyl ketone	0.72	0.00	0.45
Carbon tetrachloride	0.28	0.00	0.00
Chloroform	0.58	0.44	0.00
Ethyl acetate	0.55	0.00	0.45
Cyclopentanone	0.76	0.00	0.52
Dioxane	0.55	0.00	0.37
Acetonitrile	0.85	0.19	0.31
Acetone	0.72	0.08	0.48
Methanol	0.60	0.93	0.62
Ethanol	0.54	0.83	0.77
Ethylene glycol	0.92	0.90	0.52
Dimethyl sulfoxide	1.00	0.00	0.76
Tetrahydrofuran	0.58	0.00	0.55

The present review demonstrates how the linear solvation energy relationship method can be used to unravel, quantify, correlate and rationalize the multiple interacting effects of the selected solvent set on the reactivity parameters of carboxylic acids in their reaction with DDM.

3.1. Cycloalkenecarboxylic and cycloalkeneacetic acids

The values of the second-order rate constants for the reaction of cycloalkenecarboxylic, cycloalkeneacetic, benzoic and phenylacetic acids with DDM in 12 aprotic solvents and 3 protic solvents are given in Tables II and III.

The obtained results show that the rate constants increase with increasing solvent polarity. This is in accordance with the supposed mechanism of the reaction.[15–17,45,46]

The exceptionally high value of the reaction rate constant in chloroform could be explained by the low polarity of this solvent ($\pi^* = 0.58$) and the complete lack of proton acceptor effects, because of which the carboxylic acid dissolved in it exists in the form of dimers.[45] The dimer can appear in two forms, *i.e.*, a cyclic (I) and an open (II) form, which is a very reactive form because it can easily loose a proton and convert into a resonance-stabilized anion (III) (Fig. 2). As the carboxylic anion is the reacting form in this system, it continuously converts into products and this is the probable reason why the open chain dimer, which stabilizes the anion, is the dominant form.

In aprotic solvents of higher polarity, where the proton-acceptor effect exists, solvation of a dissolved acid does not allow the formation of any kind of

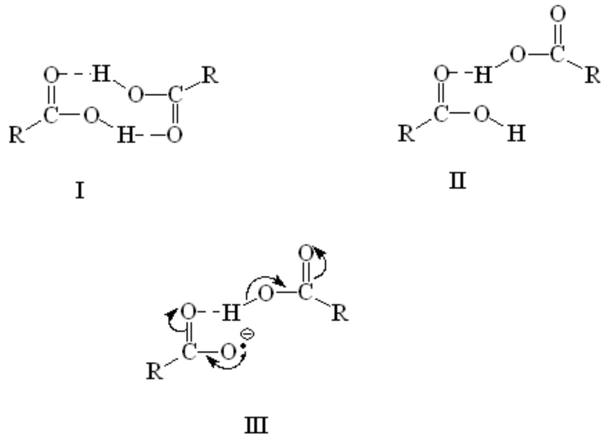
TABLE II. Second-order rate constants, dm^3 mol^{-1} min^{-1}, for the reaction of cycloalkene-carboxylic acids and benzoic acid with diazodiphenylmethane at 30 °C in various solvents

Solvent	Cyclopent-1-ene--carboxylic acid	Cyclohex-1-ene--carboxylic acid	Cyclohept-1-ene--carboxylic acid	Benzoic acid
Methyl acetate	0.044	0.032	0.031	0.260
Cyclohexanone	0.028	0.020	0.019	0.220
Diethyl ketone	0.073	0.053	0.051	0.265
Carbon tetrachloride	0.399	0.329	0.286	0.638
Chloroform	5.373	4.335	3.378	12.30
Ethyl acetate	0.038	0.025	0.016	0.180
Cyclopentanone	0.036	0.025	0.025	0.293
Dioxane	0.088	0.065	0.062	0.058
Acetonitrile	0.430	0.318	0.199	3.730
Acetone	0.059	0.048	0.039	0.350
Methanol	1.106	0.818	0.654	2.470
Ethanol	0.534	0.417	0.332	0.995
Ethylene glycol	2.452	1.962	1.570	4.020
Dimethyl sulfoxide	0.012	0.008	0.007	0.141
Tetrahydrofuran	0.027	0.019	0.016	0.105

TABLE III. Second-order rate constants, dm^3 mol^{-1} min^{-1}, for the reaction of cycloalkene-acetic acids and phenylacetic acid with diazodiphenylmethane at 30 °C in various solvents

Solvent	Cyclopent-1-ene-acetic acid	Cyclohex-1--eneacetic acid	Cyclohept-1-ene-acetic acid	Phenylacetic acid
Methyl acetate	0.181	0.144	0.098	0.132
Cyclohexanone	0.187	0.149	0.102	0.153
Diethyl ketone	0.268	0.214	0.148	0.279
Carbon tetrachloride	2.161	1.759	1.299	6.628
Chloroform	46.06	37.84	29.02	613.0
Ethyl acetate	0.036	0.028	0.017	0.210
Cyclopentanone	0.139	0.110	0.074	0.117
Dioxane	0.319	0.255	0.177	0.169
Acetonitrile	1.535	1.294	0.972	8.919
Acetone	0.246	0.194	0.146	0.233
Methanol	2.237	1.652	1.299	2.539
Ethanol	0.828	0.659	0.614	1.139
Ethylene glycol	4.080	3.020	2.237	5.049
Dimethyl sulfoxide	0.031	0.024	0.016	0.014
Tetrahydrofuran	0.071	0.056	0.039	0.057

dimer or, therefore, of the anion (III). Taking this into consideration, there still remains the question of why the reaction of carboxylic acids and DDM in other non-polar solvent, carbon tetrachloride for example (π^* = 0.28) does not proceed as fast as in chloroform. The answer could be found in the fact that the structure of chloroform includes a hydrogen atom bonded to a carbon surrounded by three electronegative chlorine molecules – therefore it has a proton-donating effect, which accelerates the reaction ($\alpha = 0.44$).



I II III

Fig. 2. Different forms of dimers of carboxylic acids that exist in non-polar aprotic solvents.

It is interesting to compare the differences in the rate constants for examined acids because strain effects due to the endocyclic double bond are responsible for prominent changes in the acid reactivity. The presence of a double bond in a five-membered ring leads to a "tension" in the system, which is in a six-membered ring, for example, relieved by folding of the molecule into the "half-chair" conformation – in a five-membered one, there is no similar effect. It was found that the cyclopentene acids have higher rate constants than the corresponding cyclohexene acids (Tables II and III). Cyclohept-1-enecarboxylic and cyclohept-1-eneacetic acids have slightly lower rate constants than the other two mentioned acid systems, which is probably due to the fact that even the slight strain present in the cyclohexene acid systems is absent from the larger seven-membered rings.

The rate constants for cycloalkeneacetic acids (Table III) in all the employed solvents were higher than those for cycloalkenecarboxylic acids in the corresponding alcohols. This is in accordance with the fact that the resonance interaction between the double bond and the carbonyl group in the cycloalkenecarboxylic acids causes a decrease in the acid strength.

In order to explain the obtained kinetic results through the solvent polarity and basicity or acidity, the rate constants were correlated with the solvatochromic parameters π^*, α and β[11] using the total solvatochromic equation, Eq. (2). The correlations of the kinetic data were realized by means of multiple linear regression analysis. It was found that the rate constants in fifteen solvents showed satisfactory correlation with the π^*,α and β solvent parameters. The obtained correlation results are as follows:

Cyclopent-1-enecarboxylic acid:

$$\log k = -0.46 + (0.42 \pm 0.18)\pi^* + (2.04 \pm 0.08)\alpha - (2.47 \pm 0.19)\beta \quad (4a)$$
$$R = 0.992,\ s = 0.13,\ n = 15.$$

Cyclohex-1-enecarboxylic acid:

$$\log k = -0.57 + (0.41 \pm 0.19)\pi^* + (2.09 \pm 0.08)\alpha - (2.54 \pm 0.16)\beta \quad (4b)$$
$$R = 0.992,\ s = 0.11,\ n = 15.$$

Cyclohept-1-enecarboxylic acid:

$$\log k = -0.63 + (0.36 \pm 0.22)\pi^* + (2.03 \pm 0.09)\alpha - (2.47 \pm 0.18)\beta \quad (4c)$$
$$R = 0.989,\ s = 0.13,\ n = 15.$$

Cyclopent-1-eneacetic acid:

$$\log k = 0.18 + (0.76 \pm 0.41)\pi^* + (1.88 \pm 0.18)\alpha - (3.22 \pm 0.34)\beta \quad (4d)$$
$$R = 0.968,\ s = 0.24,\ n = 15.$$

Cyclohex-1-eneacetic acid:

$$\log k = 0.09 + (0.77 \pm 0.42)\pi^* + (1.86 \pm 0.18)\alpha - (3.25 \pm 0.35)\beta \quad (4e)$$
$$R = 0.966,\ s = 0.25,\ n = 15.$$

Cyclohept-1-eneacetic acid:

$$\log k = -0.02 + (0.70 \pm 0.47)\pi^* + (1.95 \pm 0.20)\alpha - (3.25 \pm 0.39)\beta \quad (4f)$$
$$R = 0.961,\ s = 0.27,\ n = 15.$$

Similar results were obtained by correlating the literature kinetic data for benzoic acid[29,47] determined at 37 °C and the kinetic data determined previously for phenylacetic acid[44] (Table III). The obtained correlation results are given below:

Benzoic acid:

$$\log k = -0.58 + (1.43 \pm 0.44)\pi^* + (1.57 \pm 0.19)\alpha - (2.23 \pm 0.39)\beta \quad (5a)$$
$$R = 0.940,\ s = 0.26,\ n = 15.$$

Phenylacetic acid:

$$\log k = 0.82 + (0.92 \pm 0.57)\pi^* + (2.27 \pm 0.25)\alpha - (4.71 \pm 0.47)\beta \quad (5b)$$
$$R = 0.967,\ s = 0.33,\ n = 15.$$

From all the equations above, it can be concluded that the solvent effects influence the carboxylic acid–DDM reaction by two opposing effects. The opposite signs of the electrophilic and the nucleophilic parameters are in accordance with the described mechanism (Fig. 1). The positive signs of the s and α coefficients prove that classical solvation and HBD effects dominate the transition state and increase the reaction rate, and the negative sign of the β coefficient indicate that HBA effects stabilize the initial state before commencement of the reaction and are responsible for a decrease in the reaction rate. The degree of success of above correlations is shown in Fig. 3 by means of a plot of log k cal-

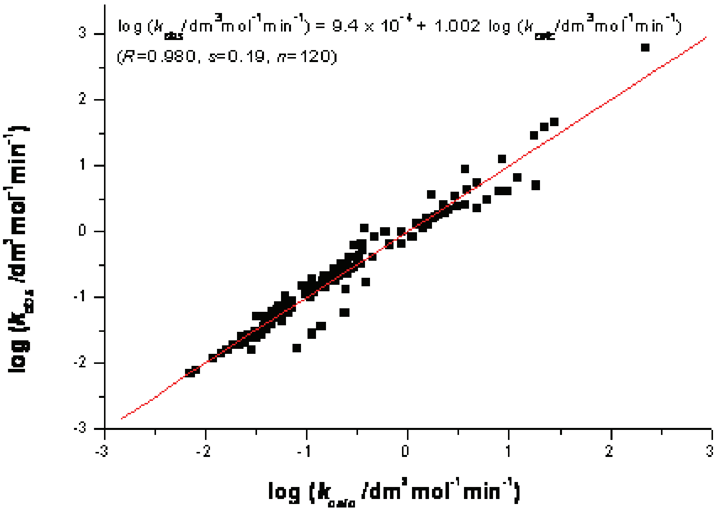


Fig. 3. The plot of *log k* observed (Tables II and III) against *log k* calculated from Eq. (2) for cycloalkenecarboxylic, cycloalkeneacetic, benzoic and phenylacetic acids in different solvents.

culated *vs*. log *k* obtained experimentally for cycloalkenecarboxylic, cycloalkeneacetic, benzoic and phenylacetic acid in different solvents. From the values of regression coefficients, the contribution of each parameter to the reactivity, on a percentage basis, were calculated and are listed in Table IV. The percentage contribution of solvatochromic parameters for the reaction of the examined acids with DDM, show that most of the solvatochromism is due to solvent basicity and acidity rather than to the solvent dipolarity/polarizability. Considering these results, the solvation models of the reactants and the transition states, separately for cycloalkenecarboxylic and cycloalkeneacetic acids can be represented as:

Cycloalkenecarboxylic acids:

Reactants	⇒	Transition state	⇒	Products
HBA solvation (≈ 50 %)		HBD and solvation by non-specific interactions (≈ 50 %)		

Cycloalkeneacetic acids:

Reactants	⇒	Transition state	⇒	Products
HBA solvation (≈ 55 %)		HBD and solvation by non-specific interactions (≈ 45 %)		

The suggested solvation models indicate that the cycloalkeneacetic acid system is more sensitive to HBA interactions of the solvent than the cycloalkenecarboxylic acid system (Table IV) and less sensitive to the HBD ability of the solvent. This is in accordance with the fact that the resonance interaction between the double bond and the carbonyl group in the case of cycloalkenecarboxylic acids destabilizes the carboxylic anion and causes a stronger solvation of the transition state in this system than in the case of cycloalkeneacetic acid system.

Table IV. The percentage contributions of the Kamlet–Taft solvatochromic parameters to the reactivity of various acids

Acid	P_{π^*} / %	P_{α} / %	P_{β} / %
Cyclopent-1-enecarboxylic	9	41	50
Cyclohex-1-enecarboxylic	8	42	50
Cyclohept-1-enecarboxylic	7	42	51
Benzoic	27	30	43
Cyclopent-1-eneacetic	13	32	55
Cyclohex-1-eneacetic	13	32	55
Cyclohept-1-eneacetic	12	33	55
Phenylacetic	12	29	59

3.2. 2-Substituted cyclohex-1-enecarboxylic and 2-substituted benzoic acids

The obtained second-order rate constants for the examined 2-substituted cyclohex-1-enecarboxylic and benzoic acids in 11 aprotic solvents (excluding chloroform), and 3 protic solvents, are given in Tables V and VI, respectively.

TABLE V. Reaction rate constants, dm^3 mol^{-1} min^{-1}, for the reaction of 2-substituted cyclohex-1-enecarboxylic acids with diazodiphenylmethane at 30 °C in various solvents

Solvent	2-Methylcyclohex-1-ene-carboxylic acid	2-Ethylcyclohex-1-ene-carboxylic acid	2-Chlorocyclohex-1-ene-carboxylic acid	2-Bromocyclohex-1-ene-carboxylic acid	2-Iodocyclohex-1-ene-carboxylic acid
Methyl acetate	0.093	0.095	0.563	0.614	0.642
Cyclohexanone	0.044	0.099	0.531	0.583	0.603
Diethyl ketone	0.064	0.110	0.583	0.634	0.653
Carbon tetrachloride	0.359	0.256	0.795	1.006	1.036
Ethyl acetate	0.058	0.082	0.501	0.574	0.606
Cyclopentanone	0.053	0.108	0.569	0.614	0.658
Dioxane	0.077	0.046	0.554	0.646	0.684
Acetone	0.106	0.116	0.680	0.831	0.891
Methanol	0.567	0.583	2.244	2.321	2.614
Ethanol	0.264	0.278	1.130	1.279	1.470
Dimethyl sulfoxide	0.013	0.060	0.198	0.210	0.230
Tetrahydrofuran	0.027	0.055	0.179	0.191	0.204
Acetonitrile	0.420	0.347	1.580	1.623	1.782
Ethylene glycol	1.631	1.649	5.222	5.169	5.738

The obtained results show that the rate constants increased with increasing solvent polarity. Comparison of the values of the reaction constants in protic and aprotic solvents indicates that the examined reaction is slower in aprotic solvents, which is in accordance with the proposed reaction mechanism.[15–17,45,46]

TABLE VI. Reaction rate constants, $dm^3\ mol^{-1}\ min^{-1}$, for the reaction of 2-substituted benzoic acids with diazodiphenylmethane at 30 °C in various solvents

Solvent	2-Methylbenzoic acid	2-Ethylbenzoic acid	2-Chlorobenzoic acid	2-Bromobenzoic acid	2-Iodobenzoic acid
Methyl acetate	0.124	0.130	1.543	1.620	1.720
Cyclohexanone	0.129	0.138	1.393	1.510	1.580
Diethyl ketone	0.157	0.160	1.510	1.690	1.760
Carbon tetrachloride	0.389	0.496	1.200	1.380	1.412
Ethyl acetate	0.094	0.106	1.479	1.480	1.590
Cyclopentanone	0.145	0.154	1.530	1.620	1.780
Dioxane	0.035	0.048	0.750	0.758	0.813
Acetone	0.152	0.170	2.087	2.440	2.680
Methanol	1.860	2.526	12.71	13.75	15.22
Ethanol	0.933	0.986	4.388	5.627	5.960
Dimethyl sulfoxide	0.079	0.072	0.512	0.522	0.586
Tetrahydrofuran	0.060	0.062	0.454	0.464	0.482
Acetonitrile	1.590	1.654	5.852	6.023	6.759
Ethylene glycol	2.590	2.680	10.69	11.08	11.84

The correlations of the kinetic data were realized by means of multiple linear regression analysis. It was found that the rate constants in the applied set of fourteen solvents showed satisfactory correlation with the π^*, α and β solvent parameters together in the same equation. The obtained correlation results are given in Table VII.

From the values of the regression coefficients, the contributions of each parameter to the reactivity, on a percentage basis, were calculated and are listed in Table VIII.

From these results, it can be noticed that the non-specific interactions (π^*) are less pronounced than the specific (α and β) in both carboxylic acid systems. However, the specific interactions have more influence on the cyclohexene system than on the benzoic system. This probably means that the carboxyl group of the cyclohexene acids is more susceptible to proton-donor and proton-acceptor solvent effects than the carboxyl group of the benzoic acids.

In order to obtain a complete view of the solvent interactions with the molecules of the examined carboxylic acids, the solvent effects were expressed quantitatively for every acid, referring separately to the reactants and the transition state and the results are given in Table IX.

Higher reaction rates and more pronounced effects of HBD solvation and non-specific interactions (polarity/polarizability) can be noticed for the halogen-substituted acids in both systems. As the negative inductive effect of the halogen at C-2 stabilizes the carboxylic anion, it supports the transition state, thus accelerating the reaction.

TABLE VII. The results of the correlations of the kinetic data for 2-substituted cyclohex-1-enecarboxylic and 2-substituted benzoic acids with Eq. (2)

Acid	s^a	a^a	b^a	R^b	s^c	F^d	n^e
Cyclohex-1-enecarboxylic acid	0.38 ± 0.20	2.07 ± 0.09	2.48 ± 0.21	0.990	0.11	168	14
2-Methylcyclohex-1-enecarboxylic acid	0.52 ± 0.16	1.66 ± 0.07	2.35 ± 0.17	0.989.	0.09	162	14
2-Ethylcyclohex-1-enecarboxylic acid	0.87 ± 0.21	1.24 ± 0.10	1.51 ± 0.22	0.972	0.12	58	14
2-Chlorocyclohex-1-enecarboxylic acid	0.75 ± 0.21	1.07 ± 0.10	1.42 ± 0.22	0.960	0.12	39	14
2-Bromocyclohex-1-enecarboxylic acid	0.64 ± 0.22	1.04± 0.10	1.42± 0.23	0.954	0.13	20	14
2-Iodocyclohex-1-enecarboxylic acid	0.65 ± 0.22	1.07 ± 0.10	1.40 ± 0.23	0.957	0.13	36	14
Benzoic acid	1.34 ± 0.47	1.51 ± 0.22	1.98 ± 0.49	0.915	0.26	17	14
2-Methylbenzoic acid	1.05 ± 0.44	1.64 ± 0.20	1.75 ± 0.46	0.932	0.25	22	14
2-Ethylbenzoic acid	0.92 ± 0.29	1.81 ± 0.13	1.79 ± 0.31	0.973	0.10	75	14
2-Chlorobenzoic acid	0.93 ± 0.19	1.28 ± 0.09	1.33 ± 0.20	0.978	0.10	75	14
2-Bromobenzoic acid	0.83 ± 0.19	1.28 ± 0.09	1.25 ± 0.20	0.976	0.11	70	14
2-Iodobenzoic acid	0.89 ± 0.19	1.31 ± 0.09	1.27 ± 0.21	0.977	0.11	71	14

[a]Calculated solvatochromic coefficient; [b]correlation coefficient; [c]standard deviation of the estimate; [d]Fisher’s test; [e]number of points used in the calculation

TABLE VIII. The percentage contributions of Kamlet–Taft’s solvatochromic parameters to the reactivity for the studied cyclohex-1-enecarboxylic acids and benzoic acids

Acid	$P_{\pi*}$ / %	P_{α} / %	P_{β} / %
Cyclohex-1-enecarboxylic acid	8	42	50
2-Methylcyclohex-1-enecarboxylic acid	11	37	52
2-Ethylcyclohex-1-enecarboxylic acid	24	34	42
2-Chlorocyclohex-1-enecarboxylic acid	23	33	44
2-Bromocyclohex-1-enecarboxylic acid	21	34	46
2-Iodocyclohex-1-enecarboxylic acid	21	34	45
Benzoic acid	28	31	41
2-Methylbenzoic acid	24	37	39
2-Ethylbenzoic acid	20	40	40
2-Chlorobenzoic acid	26	36	38
2-Bromobenzoic acid	25	38	37
2-Iodobenzoic acid	26	38	36

Considering the results presented in Table IX, the solvation models of the reactants and the transition state, considered separately for the 2-substituted cyclohex-1-enecarboxylic and 2-substituted benzoic acid systems, can be represented as:

2-Substituted cyclohex-1-enecarboxylic acids:

Reactants	⇒	Transition state	⇒	Products
HBA salvation (≈ 46 %)		HBD and solvation by non-specific interactions (≈ 54 %)		

2-Substituted benzoic acids:

Reactants	⇒	Transition state	⇒	Products
HBA salvation (≈ 38 %)		HBD and solvation by non-specific interactions (≈ 62 %)		

TABLE IX. The solvent effects for the studied cyclohex-1-enecarboxylic acids and benzoic acids

Acid	HBA solvation (*β*)/ % (effect on the reactants)	HBD solvation (*α*) + non-specific interactions (*π**)/ % (effect on the transition state)
Cyclohex-1-enecarboxylic acid	50	50
2-Methylcyclohex-1-enecarboxylic acid	52	48
2-Ethylcyclohex-1-enecarboxylic acid	42	58
2-Chlorocyclohex-1-enecarboxylic acid	44	56
2-Bromocyclohex-1-enecarboxylic acid	46	54
2-Iodocyclohex-1-enecarboxylic acid	45	55
Benzoic acid	41	59
2-Methylbenzoic acid	39	61
2-Ethylbenzoic acid	40	60
2-Chlorobenzoic acid	38	62
2-Bromobenzoic acid	37	63
2-Iodobenzoic acid	36	64

The results presented here show that the proton-acceptor solvent effects are somewhat more pronounced in the ground state for cyclohex-1-enecarboxylic acid and its 2-substituted derivatives than for benzoic acids, supporting the fact that the reaction rates were higher for the benzoic acids. The dominant solvent effects for the benzoic acid type are proton-donor and non-specific interactions, characteristic for the transition state. This fact is likely to be a consequence of the degree of conjugation of the carboxylic group of the benzoic acids with the ring; in other words, the charge distribution in the carboxylic group, which is the result of the conjugation, makes the anion more stable and, therefore, the reaction faster. However, a more general conclusion that arises from these results is that the substituents at the C-2 position in both carboxylic acid types have a secondary influence on the reaction with DDM, and seem not to cause steric hindrance between the reactants and the solvent. The principal influences on these reaction rates are apparently the properties of the solvent and the general form of the molecule of the carboxylic acid.

3.3. 2-Substituted cyclohex-1-eneacetic and 2-substituted phenylacetic acids

The values of second-order rate constants for the reaction of the examined 2-substituted cyclohex-1-eneacetic and 2-substituted phenylacetic acids with DDM in 11 aprotic and 3 protic solvents are given in Tables X and XI.

TABLE X. The second-order rate constants, dm^3 mol^{-1} min^{-1}, for the reaction of 2-substituted cyclohex-1-eneacetic acids with diazodiphenylmethane at 30 °C in various solvents

Solvent	2-Methylcyclohex-1-eneacetic acid	2-Ethylcyclohex-1-eneacetic acid	2-Chlorocyclohex-1-eneacetic acid	2-Bromocyclohex-1-eneacetic acid	2-Iodocyclohex-1-eneacetic acid	2-Nitrocyclohex-1-eneacetic acid
Methyl acetate	0.087	0.092	0.285	0.290	0.331	1.461
Cyclohexanone	0.092	0.097	0.286	0.289	0.329	1.357
Diethyl ketone	0.133	0.141	0.406	0.411	0.467	1.880
Carbon tetrachloride	1.117	1.178	3.251	3.251	3.716	14.13
Ethyl acetate	0.078	0.083	0.249	0.251	0.288	1.230
Cyclopentanone	0.066	0.071	0.216	0.217	0.251	1.096
Dioxane	0.077	0.081	0.229	0.229	0.262	1.020
Acetonitrile	0.803	0.849	2.469	2.472	2.841	11.57
Acetone	0.118	0.125	0.380	0.385	0.440	1.898
Methanol	0.890	0.942	2.479	2.669	3.212	9.682
Ethanol	0.350	0.362	0.963	1.080	1.269	4.230
Ethylene glycol	1.550	1.607	3.775	4.197	4.932	12.36
Dimethyl sulfoxide	0.018	0.019	0.038	0.042	0.067	0.242
Tetrahydrofuran	0.034	0.036	0.111	0.117	0.129	0.578

In order to explain the obtained kinetic results through solvent dipolarity/polarizability and basicity or acidity, the rate constants were correlated with the solvatochromic parameters π^*, α and β,[11] using the total solvatochromic equation, Eq. (2). The correlations of the kinetic data were realized by means of multiple linear regression analysis. It was found that the rate constants in the 14 selected solvents showed satisfactory correlation with the π^*, α and β solvent parameters. The obtained correlation results are given in Tables XII and XIII.

The percentage contribution of each solvent effect for each acid is given in Table XIV. The specific interactions, the HBA and HBD effects, are dominant and have a rather similar share for both acid types, but the classical solvation effects are somewhat higher for the phenylacetic acids, especially for its halogen- and nitro-substituted derivatives. To obtain a complete view of the solvent interaction with the molecules of the examined acids, the solvent effects are expressed quantitatively for both carboxylic acid systems and the ground and the transition state are referred to separately.

2-Substituted cyclohex-1-eneacetic acids:

Reactants		Transition state		Products
HBA solvation (≈ 57 %)	⇒	HBD and solvation by non-specific interactions (≈ 43 %)	⇒	

TABLE XI. The second-order rate constants, dm^3 mol^{-1} min^{-1}, for the reaction of 2-substituted phenylacetic acids with diazodiphenylmethane at 30 °C in various solvents

Solvent	2-(2-Methylphenyl)acetic acid	2-(2-Ethylphenyl) acetic acid	2-(2-Chlorophenyl) acetic acid	2-(2-Bromophenyl)-acetic acid	2-(2-Iodophenyl)acetic acid	2-(2-Nitrophenyl) acetic acid
Methyl acetate	0.063	0.066	0.169	0.182	0.198	0.290
Cyclohexanone	0.089	0.096	0.232	0.240	0.252	0.316
Diethyl ketone	0.165	0.168	0.358	0.364	0.376	0.560
Carbon tetrachloride	4.041	5.153	7.816	7.880	8.126	12.86
Ethyl acetate	0.109	0.124	0.273	0.286	0.294	0.462
Cyclopentanone	0.058	0.061	0.157	0.184	0.199	0.264
Dioxane	0.102	0.140	0.239	0.248	0.259	0.342
Acetonitrile	3.802	3.955	10.57	11.03	11.16	16.28
Acetone	0.101	0.113	0.348	0.360	0.384	0.486
Methanol	2.420	2.460	3.329	3.500	3.790	5.110
Ethanol	1.010	1.020	1.440	1.559	1.670	2.470
Ethylene glycol	5.333	5.457	6.761	7.261	8.035	8.750
Dimethyl sulfoxide	0.008	0.007	0.021	0.034	0.040	0.164
Tetrahydrofuran	0.033	0.033	0.092	0.098	0.134	0.198

TABLE XII. The results of the correlations of the kinetic data for 2-substituted cyclohex-1-eneacetic acids with Eq. (2)

Acid	s[a]	a[a]	b[a]	R[b]	s[c]	F[d]	n[e]
Cyclohex-1-eneacetic acid	0.40 ± 0.21	1.67± 0.10	2.73 ± 0.22	0.985	0.12	112	14
2-Methylcyclohex-1-eneacetic acid	0.50 ± 0.25	1.61± 0.12	2.71 ± 0.28	0.977	0.14	71	14
2-Ethylcyclohex-1-eneacetic acid	0.50 ± 0.25	1.60± 0.12	2.70 ± 0.27	0.977	0.14	70	14
2-Chlorocyclohex-1-eneacetic acid	0.38 ± 0.28	1.55± 0.13	2.72 ± 0.30	0.972	0.16	55	14
2-Bromocyclohex-1-eneacetic acid	0.39 ± 0.28	1.58± 0.13	2.67 ± 0.29	0.973	0.16	59	14
2-Iodocyclohex-1-eneacetic acid	0.46± 0.26	1.57± 0.12	2.60 ± 0.28	0.975	0.15	63	14
2-Nitrocyclohex-1-eneacetic acid	0.36 ± 0.30	1.58± 0.14	2.50 ± 0.32	0.962	0.17	41	14

[a]Calculated solvatochromic coefficient; [b]correlation coefficient; [c]standard deviation of the estimate; [d]Fisher's test; [e]number of points used in the calculation

2-Substituted phenylacetic acids:

Reactants	⇒	Transition state	⇒	Products
HBA solvation (≈ 58 %)		HBD and solvation by non-specific interactions (≈ 42 %)		

TABLE XIII. The results of the correlations of the kinetic data for 2-substituted phenylacetic acids with Eq. (2)

Acid	s^a	a^a	b^a	R^b	s^c	F^d	n^e
Phenylacetic acid	0.66 ± 0.52	2.08± 0.24	3.99 ± 0.55	0.952	0.29	32	14
2-(2-Methylphenyl)acetic acid	0.55± 0.47	2.36± 0.22	3.93± 0.49	0.966	0.26	47	14
2-(2-Ethylphenyl)acetic acid	0.45 ± 0.45	2.35± 0.21	4.04 ± 0.48	0.969	0.25	51	14
2-(2-Chlorophenyl)acetic acid	0.67 ± 0.49	2.03± 0.23	3.85 ± 0.52	0.983	0.12	96	14
2-(2-Bromophenyl)acetic acid	0.76 ± 0.47	1.98± 0.22	3.71 ± 0.50	0.954	0.28	34	14
2-(2-Iodophenyl)acetic acid	0.75 ± 0.46	1.96± 0.21	3.61 ± 0.48	0.952	0.26	35	14
2-(2-Nitrophenyl)acetic acid	0.82 ± 0.54	1.79± 0.25	3.31 ± 0.56	0.929	0.30	22	14

[a]Calculated solvatochromic coefficient; [b]correlation coefficient; [c]standard deviation of the estimate; [d]Fisher's test; [e]number of points used in the calculation

TABLE XIV. The percentage contributions of the Kamlet-Taft solvatochromic parameters to the reactivity

Acid	P_{π^*} / %	P_{α} / %	P_{β} / %
Cyclohex-1-eneacetic acid	8	35	57
2-Methylcyclohex-1-eneacetic acid	10	33	57
2-Ethylcyclohex-1-eneacetic acid	10	33	57
2-Chlorocyclohex-1-eneacetic acid	8	33	59
2-Bromocyclohex-1-eneacetic acid	8	34	58
2-Iodocyclohex-1-eneacetic acid	10	34	56
2-Nitrocyclohex-1-eneacetic acid	8	36	56
Phenylacetic acid	10	31	59
2-(2-Methylphenyl)acetic acid	8	35	57
2-(2-Ethylphenyl)acetic acid	7	35	58
2-(2-Chlorophenyl)acetic acid	10	31	59
2-(2-Bromophenyl)acetic acid	12	31	57
2-(2-Iodophenyl)acetic acid	12	31	57
2-(2-Nitrophenyl)acetic acid	14	30	56

It can be noticed that the two examined carboxylic acid types behave similarly, as can be seen from the distributions of solvent effects that are practically the same. However, the more general conclusion that arises from these results is that the substituents at the C-2 position in both carboxylic acid types have a very weak influence on the solvation effects during reaction with DDM. The phenylacetic acids are somewhat faster than the corresponding cyclohexeneacetic ones, which makes sense, as their structure is more approachable for the other reactant as well as for solvent, but there seems to be no great difference. On the contrary, in the case of the α,β-unsaturated cyclic carboxylic acids there was a considerable difference between the reaction rate constants of benzoic and cyclohex-1-enecarboxylic acids regardless of the presence of substituents.[42,43] In other words, the ring type determines the reactivity of a carboxylic acid. For β,γ-unsaturated acids, the ring is sufficiently far removed from the reaction center (the carboxylic group) to have much influence on it, hence the steric and electronic effects of substituents in the γ-position are more visible. Regarding the geometric properties, the 2-substituted cyclohex-1-eneacetic acids and 2-substituted phenylacetic acids have similar torsion angles, as well as the reactivity, but the α,β-unsaturated cyclic carboxylic acids (benzoic and cyclohex-1-enecarboxylic) have completely a different geometry and, subsequently, behave differently in the same reaction. The torsion angle (C_2–C_3–C_4) for benzoic acid is –16.60° and for cyclohex-1-enecarboxylic acid 142.0°. Their values are very different and the carboxylic groups are orientated in opposing directions.[43]

3.4. 2-Phenylcyclohex-1-enecarboxylic, 2-phenylbenzoic and 2-phenylacrylic acids

The transmission of substituent effects through three types of double bond, *i.e.*, in a ring, open chain and delocalized double bonds, were investigated previously in the case of 2-(4-substitutedphenyl)cyclohex-1-enecarboxylic acids,[33,35] 2-(4-substitutedphenyl)benzoic acids[33,48] and 2-(4-substitutedphenyl)acrylic acids.[33,35] The results showed that there were differences in the composition of the electronic effect depending on the type of double bond through which the substituent effects were transmitted. The considerable difference between the reaction constants, ρ, of the investigated acids indicates that, regardless of the identical possibility of steric interactions of the phenylene and the carboxylic group, there is probably a different interaction of the phenylene group with the rest of the molecule. This assumption was confirmed with Dreiding models.

In the present review, the values of the second order rate constants for the reaction of 2-phenylcyclohex-1-enecarboxylic, 2-phenylbenzoic and 2-phenylacrylic acids with DDM in 11 aprotic and 3 protic solvents (Table XV) were correlated with the solvatochromic parameters π^*, α and β using the total solvatochromic equation. The correlation of the kinetic data was realized by means of multiple linear regression analysis.

It was found that the rate constants in 14 solvents showed satisfactory correlation with the solvatochromic parameters π^*, α and β. The obtained correlation results were as follows:

2-Phenylcyclohex-1-enecarboxylic acid:

$$\log k = -0.14 + (0.35 \pm 0.22)\pi^* + (2.34 \pm 0.10)\alpha - (2.70 \pm 0.24)\beta \qquad (6a)$$
$$(R = 0.991,\ s = 0.13,\ F = 175,\ n = 14).$$

2-Phenylbenzoic acid:

$$\log k = -0.34 + (0.99 \pm 0.41)\pi^* + (2.11 \pm 0.19)\alpha - (1.90 \pm 0.44)\beta \qquad (6b)$$
$$(R = 0.961,\ s = 0.24,\ F = 40,\ n = 14).$$

2-Phenylacrylic acid:

$$\log k = 0.24 + (0.29 \pm 0.19)\pi^* + (1.92 \pm 0.09)\alpha - (2.23 \pm 0.21)\beta \qquad (6c)$$
$$(R = 0.989,\ s = 0.11,\ F = 151,\ n = 14).$$

TABLE XV. The second-order rate constants, $dm^3 mol^{-1} min^{-1}$, for the reaction of 2-phenylcyclohex-1-enecarboxylic, 2-phenylbenzoic and 2-phenylacrylic acids with diazodiphenylmethane at 30 °C in various solvents

Solvent	2-Phenylcyclohex-1-enecarboxylic acid	2-Phenylbenzoic acid	2-Phenylacrylic acid
Methyl acetate	0.068	0.316	0.244
Cyclohexanone	0.038	0.246	0.151
Diethyl ketone	0.133	0.268	0.424
Carbon tetrachloride	0.873	1.010	2.001
Ethyl acetate	0.054	0.236	0.201
Cyclopentanone	0.049	0.338	0.186
Dioxane	0.142	0.110	0.447
Acetonitrile	0.839	5.500	1.937
Acetone	0.103	0.400	0.343
Methanol	2.790	11.61	5.219
Ethanol	1.279	5.000	2.743
Ethylene glycol	6.367	15.37	10.31
Dimethyl sulfoxide	0.014	0.162	0.066
Tetrahydrofuran	0.037	0.147	0.147

From all the equations above, it can be concluded that two opposing solvent effects influence the carboxylic acid – DDM reaction. The opposite signs of the electrophilic and the nucleophilic parameters are in accordance with the described mechanism (Fig. 1). The positive signs of the coefficients *s* and *a* prove that classical solvation and the HBD effects dominate the transition state and increase the reaction rate, and the negative sign of the coefficient *b* indicates that HBA effects stabilize the initial state before the reaction commences and are responsible for a decrease in the reaction rate. From the values of the regression coefficients, the contribution of each parameter to the reactivity, on a percentage basis, were calculated and are listed in Table XVI. The percentage contribution of the solvatochromic parameters for the reaction of the examined acids with DDM show that most of the solvatochromism is due to solvent basicity and acidity rather than to the solvent dipolarity/polarizability. Considering these results, the solvation models of the reactants and the transition states, separately for 2-phenylcyclohex-1-enecarboxylic, 2-phenylbenzoic and 2-phenylacrylic acids can be represented as:

2-Phenylcyclohex-1-enecarboxylic acids:

Reactants	⇒	Transition state	⇒	Products
HBA solvation (≈ 50 %)		HBD and solvation by non-specific interactions (≈ 50 %)		

2-Phenylbenzoic acids:

Reactants	⇒	Transition state	⇒	Products
HBA solvation (≈ 38 %)		HBD and solvation by non-specific interactions (≈ 62 %)		

2-Phenylacrylic acids:

Reactants	⇒	Transition state	⇒	Products
HBA solvation (≈ 50 %)		HBD and solvation by non-specific interactions (≈ 50 %)		

TABLE XVI. The percentage contributions of the Kamlet–Taft solvatochromic parameters to the reactivity

Acid	P_{π^*} / %	P_{α} / %	P_{β} / %
2-Phenylcyclohex-1-enecarboxylic	6.50	43.50	50.00
2-Phenylbenzoic	20.00	42.00	38.00
2-Phenylacrylic	6.50	43.50	50.00

The suggested solvation models indicate that the 2-phenylcyclohex-1-enecarboxylic and the 2-phenylacrylic acid systems are more sensitive to HBA solvent interactions than the 2-phenylbenzoic acid system (Table XVI) and less sensitive to the HBD solvent ability. The same results were obtained for a comparative LSER study of the reactivity of 2-substituted cyclohex-1-enecarboxylic and 2-substituted benzoic acids[43] and 2-substituted cyclohex-1-eneacetic and 2-substituted phenylacetic acids[44] presented in this review.

Generally, the presence of a substituent at the C-2 position in all types of examined acids affects the orientation of the carboxylic group. The degree of these interactions is in agreement with the obtained kinetic data, solvation models and characteristics of the examined carboxylic acid molecules.[42–44]

4. CONCLUDING REMARKS

The results of the presented investigations show that the solvatochromic concept of Kamlet and Taft (LSER) is applicable to the kinetic data for the reaction of more than 50 different carboxylic acids with diazodiphenylmethane in various solvents, meaning that this model gives the correct interpretation of the solvating effects on the carboxylic group in the selected solvents. For these reasons, it is considered that the results presented in this review may be used to quantitatively estimate and separate the overall solvent effects into the contributions of the initial and the transition state in the reaction of diazodiphenylmethane with carboxylic acids, and the solvation models are proposed. The results show that substituents at the C-2 position of the ring in all types of the investigated acids have a secondary influence on the reaction with DDM and do not seem to cause steric hindrance between the reactants and the solvent. The reactivities of the examined carboxylic acids in the reaction with DDM are in agreement with their geometric characteristics.

Acknowledgements. The authors acknowledge the financial support of the Ministry of Science and Technological Development of the Republic of Serbia (Project 142063).

ИЗВОД

ПРОУЧАВАЊЕ РЕАКТИВНОСТИ КАРБОКСИЛНИХ КИСЕЛИНА СА ДИАЗОДИФЕНИЛМЕТАНОМ У АПРОТИЧНИМ И ПРОТИЧНИМ РАСТВАРАЧИМА ПОМОЋУ ЛИНЕАРНЕ КОРЕЛАЦИЈЕ СОЛВАТАЦИОНИХ ЕНЕРГИЈА

ГОРДАНА С. УШЋУМЛИЋ и ЈАСМИНА Б. НИКОЛИЋ

Катедра за органску хемију, Технолошко–металуршки факултет Универзитета у Београду, Карнегијева 4, п. пр. 3503, 11120 Београд

Утицај растварача на реактивност циклоалкенкарбонских, циклоалкенсирћетних, 2-супституисаних циклохекс-1-енкарбонских, 2-супституисаних циклохекс-1-енсирћетних, 2-супституисаних бензоевих, 2-супституисаних фенилсирћетних, 2-фенилциклохекс-1-енкарбонске, 2-фенилбензоеве и 2-фенилакрилне киселине са диазодифенилметаном је проучаван у низу протичних и апротичних растварача. Да би се кинетички резултати објаснили помоћу ефеката растварача, добијене константе брзине реакције другог реда су корелисане помоћу Камлет–Тафтове солватохромне једначине. Корелације кинетичких података су извршене помоћу методе вишеструке линеарне регресионе анализе, а ефекти растварача су посебно анализирани у односу на основно и прелазно стање. Аритметички знаци испред коефицијената солватохромних параметара одговарају претпостављеном механизму испитиване реакције. Предложен је солватациони модел за све проучаване киселине, који је показао да постоји квантитативни однос молекулске структуре и њихове реактивности.

(Примљено 15. јуна 2009)

REFERENCES

1. E. D. Hughes, C. K. Ingold, *J. Chem. Soc.* (1935) 244
2. J. G. Kirkwood, *J. Phys. Chem.* **2** (1934) 351
3. E. Grunwald, S. Winstein, *J. Am. Chem. Soc.* **70** (1948) 846
4. M. H. Abraham, *Prog. Phys. Org. Chem.* **11** (1974) 1
5. E. F. Caldin, *Pure Appl. Chem.* **51** (1979) 2067
6. C. Reichardt, *Pure Appl. Chem.* **54** (1982) 1867
7. D. Mather, J. Shorter, *J. Chem. Soc. Perkin Trans. 2* (1983) 1179
8. I. A. Koppel, V. A. Palm, in *Advanced Linear Free Energy Relationships*, N. B. Chapman, J. Shorter, Eds., Plenum Press, London, 1972, Ch. 5
9. M. J. Kamlet, J. L. M. Abboud, R. W. Taft, *Prog. Phys. Org. Chem.* **13** (1981) 485
10. M. H. Abraham, R. W. Taft, M. J. Kamlet, *J. Org. Chem.* **46** (1981) 3053
11. M. J. Kamlet, J. L. M. Abboud, M. H. Abraham, R. W. Taft, *J. Org. Chem.* **48** (1983) 2877
12. M. H. Abraham, *Pure Appl. Chem.* **57** (1985) 1055
13. M. H. Aslan, A. G. Burden, N. B. Chapman, J. Shorter, *J. Chem. Soc. Perkin Trans. 2* (1981) 500
14. M. H. Aslan, G. Collier, J. Shorter, *J. Chem. Soc. Perkin Trans. 2* (1981) 1572
15. K. Bowden, N. B. Chapman, J. Shorter, *J. Chem. Soc.* (1963) 5329

16. J. Shorter, *Correlation Analysis of Organic Reactivity,* Wiley, Chichester, UK, 1982, p. 130
17. M. H. Abraham, L. P. Grellier, J. L. M. Abboud, M. R. Doherty, R. W. Taft, *Can. J. Chem.* **66** (1988) 2673
18. G. S. Uščumlić, V. V. Krstić, M. D. Muškatirović, *J. Serb. Chem. Soc.* **54** (1989) 119
19. G. S. Uščumlić, V. V. Krstić, M. D. Muškatirović *J. Chem. Soc. Perkin Trans. 2* (1993) 999
20. G. S. Uščumlić, J. B. Nikolić, V. V. Krstić, *Indian J. Chem. B* **44** (2005) 1283
21. G. S. Uščumlić, M. D. Muškatirović, *J. Serb. Chem. Soc.* **59** (1994) 803
22. G. S. Uščumlić, M. D. Muškatirović *J. Chem. Soc. Perkin Trans. 2* (1994) 1799
23. J. B. Nikolić, G. S. Uščumlić, V. V. Krstić, *J. Serb. Chem. Soc.* **69** (2004) 601
24. G. S. Uščumlić, V. V. Krstić, M. D. Muškatirović, *J. Serb. Chem. Soc.* **50** (1985) 343
25. J. B. Nikolić, G. S. Uščumlić, V. V. Krstić, *Indian J. Chem. B* **43** (2004) 1995
26. J. B. Nikolić, G. S. Uščumlić, V. V. Krstić, in *Recent Progress in Medicinal Plants,* Stadium Press, Houston, TX, Vol. 14, 2006, p. 71
27. G. S. Uščumlić, V. V. Krstić, M. D. Muškatirović, *J. Serb. Chem. Soc.* **58** (1993) 881
28. G. S. Uščumlić, J. B. Nikolić, V. V. Krstić, *J. Serb. Chem. Soc.* **67** (2002) 77
29. N. B. Chapman, M. R. J. Dack, J. Shorter, *J. Chem. Soc. B* (1971) 834
30. G. S. Uščumlić, V. V. Krstić, M. D. Muškatirović, *J. Mol. Struct.* **174** (1988) 521
31. V. V. Krstić, G. S. Uščumlić, M. D. Muškatirović, *J. Mol. Struct.* **174** (1988) 247
32. G. S. Uščumlić, V. V. Krstić, M. D. Muškatirović, *J. Serb. Chem. Soc.* **59** (1994) 889
33. G. S. Uščumlić, V. V. Krstić, *J. Serb. Chem. Soc.* **61** (1996) 411
34. G. S. Uščumlić, V. V. Krstić, *J. Serb. Chem. Soc.* **61** (1996) 621
35. G. S. Uščumlić, V. V. Krstić, M. D. Muškatirović, *Quant. Struct. Act. Relat.* **10** (1991) 216
36. G. S. Uščumlić, V. V. Krstić, M. D. Muškatirović, *J. Serb. Chem. Soc.* **60** (1995) 181
37. G. S. Uščumlić, V. V. Krstić, *Indian J. Chem. B* **37** (1998) 85
38. G. S. Uščumlić, V. V. Krstić, *Org. React.* **31** (1997) 181
39. G. S. Uščumlić, M. D. Muškatirović, *J. Serb. Chem. Soc.* **56** (1991) 707
40. G. S. Uščumlić, M. D. Muškatirović, *J. Serb. Chem. Soc.* **57** (1992) 19
41. J. B. Nikolić, G. S. Uščumlić, V. V. Krstić, *Int. J. Chem. Kinet.* **37** (2005) 361
42. J. B. Nikolić, G. S. Uščumlić, I. O. Juranić, *Int. J. Chem. Kinet.* **39** (2007) 664
43. J. B. Nikolić, G. S. Uščumlić, *J. Serb. Chem. Soc.* **72** (2007) 1217
44. J. B. Nikolić, G. S. Uščumlić, I. O. Juranić, *Int. J. Chem. Kinet.* **41** (2009) 613
45. N. B. Chapman, M. R. J. Dack, D. J. Newman, J. Shorter, R. Wilkinson, *J. Chem. Soc. Perkin Trans. 2* (1974) 962
46. N. B. Chapman, D. J. Newman, J. Shorter, *J. Chem. Soc. Perkin Trans. 2* (1976) 847
47. C. Reinchart, *Solvents and Solvent Effects in Organic Chemistry,* Wiley-VCH, Weinheim, Germany, 2003, p. 447
48. K. Bowden, M. Hojatti, *J. Chem. Soc. Perkin Trans. 2* (1990) 1201.