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Use of Quantitative Structure–Property Relationships in Predicting the Krafft Point of Anionic Surfactants

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Use of Quantitative Structure–Property Relationships in Predicting the Krafft Point of Anionic Surfactants[#]

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Abstract

Motivation. The Krafft point is the temperature at which the solubility of hydrated surfactants crystals increases sharply with increasing temperature. Also, the concentration at which micelles are formed at the Krafft temperature is the critical micelle concentration (CMC). Therefore, knowing the Krafft point and CMC of the surfactants is important and one should have information about the conditions in which a surfactant acts. This is useful to select an appropriate surfactant for a special application.

Method. The linear relationship between the descriptors and Krafft point of anionic surfactants was modeled using multiple linear regression technique. Linear models were generated using a stepwise regression model.

Results. A set of 32 linear alkyl sulfates [RSO₄Na] and sulfonates [RSO₃Na], sulfates and sulfonates with an ether or ester linkage to the hydrophobic tail [R(OCH₂CH₂)_nSO₄Na], [RCOO(CH₂)_nSO₃Na] were used for model generation. Among different models, two equations were selected for their good statistical results. Specification of the best model in agreement with the experiment indicates that four descriptors consisting of the Randić index, heat of formation, reciprocal of the dipole moment, and reciprocal of the volume of tail of the molecule play a major role in the prediction of Krafft point of anionic surfactants. The statistics of the best models together with the cross-validation results indicate the capability of both models in predicting the Krafft point of anionic surfactants. Different strategies, including the Akaike Information Criterion (AIC), were used for choosing the best model.

Conclusions. It was demonstrated that the Krafft point of these compounds depends on electronic descriptors and topological characteristics, such as compactness and branching of anionic surfactants.

Keywords. Anionic surfactants; Krafft point; alkylsulphates; alkylsulphonates; multiple linear regression; quantitative structure–property relationships; QSPR; computer modeling.

Abbreviations and notations

DIP ⁻¹ , reciprocal of the dipole moment	<i>r</i> , correlation coefficient
HEAT, heat of formation	RA, Randić index
Krafft, Krafft point	<i>s</i> , standard deviation
MLR, multiple linear regression	VT ⁻¹ , reciprocal of volume of the tail of the molecule
AIC, Akaike Information Criterion	CMC, critical micelle concentration
QSPR, quantitative structure–property relationships	

[#] Dedicated to Professor Milan Randić on the occasion of the 70th birthday.

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1 INTRODUCTION

The Krafft point is an important physical property of ionic surfactants, establishing the minimum temperature at which a surfactant can be used. The solubility of ionic surfactants in water is influenced by temperature, and the Krafft point is the temperature at which a hydrated surfactant crystalline solid melts and forms micelles in solution. Below this temperature, there are surfactant monomers in solution, in equilibrium with the solid, but the concentration is below CMC so the solubility is limited. If a micellar solution is cooled below the Krafft point, it will precipitate out of solution and detergency of the solution will be lost. The solubility slowly increases as the temperature rises up to the Krafft temperature, after which there is a very rapid rise in solubility, and micelles form in solution. Thus, it is desirable to make formulations at above the Krafft temperature if complete solubility is required [1–2]. Also, the concentration at which micelles are formed at the Krafft temperature is the critical micelle concentration (CMC). Therefore, knowing the Krafft point and CMC of the surfactants is important and one should have information about the conditions in which a surfactant acts. This is useful to select an appropriate surfactant for a special application [3]. Several aspects regarding the influence of the molecular structure on the Krafft point are known. For a wide variety of anionic surfactants, the Krafft point increases on average 5.5 °C for each methylene (–CH₂–) group in the hydrophobic tail. Also, for the one case available, there is an average decrease of 9 °C per ethylene oxide residue (–CH₂–CH₂O–) in the hydrophilic head group. Finally, no systematic formula could be developed for the influence of the head group, therefore, the counterion plays a significant role and can change the Krafft point by over 10 °C. It is interesting to note that as it has also been established that there is a linear relationship between the logarithm of CMC and the carbon number, it follows that there is a linear relationship between the Krafft point and log CMC for a given homologous series of surfactants [4].

In order to study the influence of the molecular structure on the Krafft point, it is desirable to develop the largest possible set of surfactants with reliable Krafft point measurements. Due to the limited amount of Krafft point data in the literature, this effort focused on anionic surfactants that were sodium salts. Sodium is the most prevalent counterion, and if structure–property relationships can be generally developed for this subset, it provides a good base to expand the study to examine specific counterion effects [5–6]. The theoretical investigations and computer modeling of the Krafft point is very limited in the literature. Therefore, the development of a theoretical model for calculation of the Krafft point seems to be necessary.

2 MATERIALS AND METHODS

The relationship between the Krafft point of anionic surfactants and the numerical encoded structural parameters (descriptors) as independent variables was modeled using multiple linear regression (MLR) method. The strategy used in this study consists of three fundamental stages:

(a) selection of data set, (b) molecular descriptor generation and (c) regression analysis. The topological and geometric descriptors were calculated using FORTRAN programs developed in our laboratory. The SPSS/PC package [7] was used for regression calculations. The MOPAC (version 6.0) [8] and HyperChem [9] packages were employed for optimization of the structure of the molecules and calculations of some electronic descriptors.

2.1 Krafft Point Data

The data set used for modeling the Krafft point of anionic surfactants was a set of thirty-two linear alkyl sulfates [RSO₄Na] and sulfonates [RSO₃Na], sulfates and sulfonates with an ether or ester linkage to the hydrophobic tail [R(OCH₂CH₂)_nSO₄Na], [RCOO(CH₂)₂SO₃Na] taken from literature [10]. It can be seen from Table 1 that the structures of the selected anionic surfactants are very diverse.

Table 1. Structure of the Chemical Compounds

No	Compound	No	Compound	No	Compound
1	C ₁₀ H ₂₁ SO ₄ Na	12	2-MeC ₁₇ H ₃₅ SO ₄ Na	23	C ₁₀ H ₂₁ COO(CH ₂) ₂ SO ₃ Na
2	C ₁₁ H ₂₃ SO ₄ Na	13	C ₁₀ H ₂₁ SO ₃ Na	24	C ₁₂ H ₂₅ COO(CH ₂) ₂ SO ₃ Na
3	C ₁₂ H ₂₅ SO ₄ Na	14	C ₁₂ H ₂₅ SO ₃ Na	25	C ₁₄ H ₂₉ COO(CH ₂) ₂ SO ₃ Na
4	2-MeC ₁₃ H ₂₇ SO ₄ Na	15	C ₁₃ H ₂₇ SO ₃ Na	26	C ₈ H ₁₇ OOC(CH ₂) ₂ SO ₃ Na
5	C ₁₃ H ₂₇ SO ₄ Na	16	C ₁₄ H ₂₉ SO ₃ Na	27	C ₁₀ H ₂₁ OOC(CH ₂) ₂ SO ₃ Na
6	C ₁₄ H ₂₉ SO ₄ Na	17	C ₁₅ H ₃₁ SO ₃ Na	28	C ₁₂ H ₂₅ OOC(CH ₂) ₂ SO ₃ Na
7	C ₁₅ H ₃₁ SO ₄ Na	18	C ₁₆ H ₃₃ SO ₃ Na	29	C ₁₄ H ₂₉ OOC(CH ₂) ₂ SO ₃ Na
8	C ₁₆ H ₃₃ SO ₄ Na	19	C ₁₇ H ₃₅ SO ₃ Na	30	C ₁₆ H ₃₃ OCH ₂ CH ₂ SO ₄ Na
9	2-MeC ₁₅ H ₃₁ SO ₄ Na	20	C ₁₈ H ₃₇ SO ₃ Na	31	C ₁₆ H ₃₃ (OCH ₂ CH ₂) ₂ SO ₄ Na
10	C ₁₇ H ₃₅ SO ₄ Na	21	C ₁₂ H ₂₅ CH(OH)C ₂ H ₅ SO ₃ Na	32	C ₁₆ H ₃₃ (OCH ₂ CH ₂) ₃ SO ₄ Na
11	C ₁₈ H ₃₇ SO ₄ Na	22	C ₈ H ₁₇ COO(CH ₂) ₂ SO ₃ Na		

2.2 Structural Descriptors

In the present work, a total of 24 separate molecular structural descriptors were calculated for each compound in the data set. These descriptors consist of topological, geometric, and electronic structural descriptors. The four descriptors appearing in the best model are: the Randić index (RA) [11] as a topological descriptor, heat of formation (HEAT) and reciprocal of the dipole moment of the molecules (DIP⁻¹) as electronic descriptors, and reciprocal of the volume of the tail of the molecule (VT⁻¹) as a geometric descriptor. In order to calculate the geometric and electronic descriptors, the structure of molecules was fully optimized using AM1 SCF-MO method [12]. For this purpose, the AM1 Hamiltonian was used as implemented in the MOPAC (version 6.0) [8] and HyperChem [9] packages. All calculations were performed at high precision with a GNORM = 0.1.

2.3 Generation and Evaluation of the Regression Models

The linear relationship between the descriptors and the Krafft point of anionic surfactants was modeled using Multiple Linear Regression, MLR, technique. In order to develop this relationship, linear and quadratic terms were used without the use of cross terms. Linear models were generated

using a stepwise regression method [13].

In practice, there are many ways for the choice of which equation to consider further. One way that we have incorporated in our previous works [14–15] is considering of four criteria of correlation coefficient (r), standard deviation (s), F value for the statistical significance of the model and the ratio of the number of observations to the number of descriptors in the equation. According to this strategy, an ideal model is one having a high r and F values, low standard deviation, and the smallest number of independent descriptors. To test the validity of the models, a cross-validation procedure was used. For each model, a number of molecules equal to the number of descriptors appearing in the model were eliminated from the data set each time and then a model was developed using the remaining compounds. Another way for choosing the best model is the use of Akaike Information Criterion (AIC) [16]. This method considers the lack of fit together with the number of descriptors from the model. AIC includes the sum of squares of residuals (SSR), the number of experimental points n , and the number of terms of the model q :

$$\text{AIC} = n \cdot \ln \frac{\text{SSR}}{n} + 2q \quad (1)$$

The most suitable model is the one that gives the lowest value of AIC. In this work we have obtained similar results using both strategies.

3 RESULTS AND DISCUSSION

A number of good models were obtained using the experimental Krafft point values as dependent variables and the calculated descriptors as independent variables. Among these equations two models were selected as the bests and their specifications are given in Tables 2 and 3. These models were selected due to their high values of R and F statistics and low standard deviations.

Table 2. Statistics for the MLR Model 1.^a

Descriptor	Notation	Coefficient	Mean effect
Randić Index	RA	7.146 (±1.892)	59.408
Heat of formation	HEAT	0.346 (±0.022)	−109.263
Reciprocal of dipole moment	DIP ^{−1}	−1507.87 (±362.045)	−42.989
Constant		121.438	

^a The statistics for this equation are: $r = 0.967$, $s = 4.137$ and $F = 136$, $r^2_{\text{Cross-Validation}} = 0.863$, $\text{AIC} = 92.653$

Table 3. Statistics for the MLR Model 2.^a

Descriptor	Notation	Coefficient	Mean effect
Randić Index	RA	10.472 (±1.892)	83.448
Heat of formation	HEAT	0.355 (±0.022)	−112.105
Reciprocal of volume of tail of the molecule	VT ^{−1}	9039.187 (±4408.456)	35.478
Reciprocal of dipole moment	DIP ^{−1}	−1826.331 (±376.484)	−53.398
Constant		70.310	

^a The statistics for this equation are: $r = 0.972$, $s = 3.919$ and $F = 115$, $r^2_{\text{Cross-Validation}} = 0.883$, $\text{AIC} = 89.92$

A comparison of the statistics for the models 1 and 2 given in Tables 2 and 3, respectively, reveals the superiority of the model 2 over that of the model 1. However, a lower number of descriptors (3 parameters) from model 1 compared with model 2 (4 parameters) and its statistics reveal that this equation also represents a good model for predicting of the Krafft point for anionic surfactants. The models 1 and 2 have three parameters in common: the Randić index (RA), the reciprocal of dipole moment of the molecule (DIP^{-1}), and heat of formation (HEAT) in common.

Table 4. Correlation Coefficients between the Descriptors in Models 1 and 2

Descriptor	Krafft	DIP^{-1}	HEAT	RA	VT^{-1}
Krafft	1.000				
DIP^{-1}	0.592	1.000			
HEAT	0.180	0.650	1.000		
RA	0.498	-0.952	-0.735	1.000	
VT^{-1}	0.536	0.957	0.669	-0.971	1.000

Table 5. Descriptors, Experimental and Calculated Values of the Krafft Point

No ^a	Descriptors				Krafft point		
	RA	VT^{-1}	DIP^{-1}	HEAT	Model 1	Model 2	Exp
1	6.3796	0.0051	0.0382	-296.10	5.8	8.6	7
2	6.8896	0.0047	0.0346	-302.96	13.69	15.2	16
3	7.7734	0.0041	0.0358	-314.31	13.5	10.1	11
4	7.8796	0.0044	0.0316	-309.81	24.00	26.9	20.8
5	7.8796	0.0041	0.0290	-316.66	26.2	26.00	21
6	8.3796	0.0038	0.0268	-335.52	26.5	18.5	31.5
7	8.8796	0.0036	0.0249	-330.37	35.9	35.7	31
8	8.7734	0.0036	0.0302	-328.01	26.0	23.3	25
9	9.3796	0.0034	0.0233	-337.22	39.7	38.2	38.2
10	9.8796	0.0032	0.0218	-344.07	43.7	43.7	40.5
11	9.7734	0.0032	0.0260	-341.72	35.9	35.4	30
12	5.9319	0.0056	0.0427	-289.25	-3.3	-2.0	8
13	5.7488	0.0056	0.0443	-226.80	17.1	20.7	22
14	6.7488	0.0047	0.0357	-240.51	35.3	36.4	33
15	7.2488	0.0044	0.0325	-247.36	42.4	43.4	35.5
16	7.7488	0.0041	0.0298	-254.22	48.5	48.2	42
17	8.2488	0.0038	0.0275	-261.07	53.8	54.4	48
18	8.7488	0.0036	0.0255	-267.92	58.6	58.9	50
19	9.2488	0.0034	0.0238	-274.77	62.8	63.5	62
20	9.7488	0.0032	0.0223	-281.62	66.6	68.0	57
21	8.3009	0.0037	0.0340	-307.15	23.6	18.8	20.2
22	6.4171	0.0048	0.0375	-306.50	3.3	3.1	0
23	7.4171	0.0042	0.0312	-320.35	17.1	14.9	8.1
24	8.4171	0.0037	0.0268	-334.07	27.4	25.2	24.2
25	9.4171	0.0033	0.0233	-347.75	36.0	36.0	36.2
26	6.4171	0.0048	0.0384	-307.87	1.1	-0.8	0
27	7.4171	0.0042	0.0321	-321.57	14.9	12.4	12.5
28	8.4171	0.0037	0.0274	-335.27	25.8	24.3	26.5
29	9.4171	0.0033	0.0238	-348.98	34.6	33.2	39
30	9.9570	0.0031	0.0210	-378.55	32.1	31.5	36
31	11.034	0.0027	0.0180	-425.24	27.3	29.6	24
32	12.111	0.0025	0.0158	-471.64	21.0	28.7	19

^a The structure of the compounds is given in Table 1

Table 4 shows the correlation between all independent variables appearing in the model 1. It can be seen from this table that Randić index (RA) and reciprocal of dipole moment of the molecule (DIP^{-1}) show a high correlation of 0.952 with each other, but each parameter encodes different aspects of the molecular structure. Model 2 has a better statistic specification but has an additional parameter, namely the reciprocal volume of the tail of the molecule. It can be seen from Table 4 that this parameter shows a high correlation with the Randić index and the reciprocal of the dipole moment. Therefore, it does not bring different aspects of molecular structure (with VT^{-1} and RA) so that it is better to select the model 1.

Comparison of the mean effects of the descriptors appearing in these models show that the heat of formation of the molecules has the largest effect on the Krafft point of the anionic surfactants. The mean effect of a descriptor is the product of its mean and the regression coefficient in the MLR model. An inspection of the Table 5 indicates that as the length of chain increases the heat of formation decreases and the Krafft point of the molecules increases. The negative effect of this parameter is in agreement with the experiment. An increase in the chain length of the hydrophobic portion increases the hydrophobic tendency of this part of the molecule and leads to a lower aqueous solubility. This means that the Krafft point will be shifted to a higher temperature (molecules 1–8).

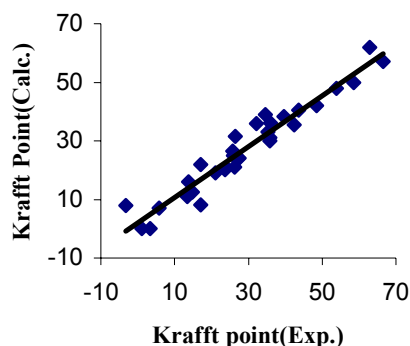


Figure 1. Plot of calculated *versus* experimental values of the Krafft point for model 1.

The Randić index quantifies the molecular branching and compactness of molecules and shows a considerable positive mean effect on the Krafft point of the anionic surfactants (Table 3). This is in agreement with the experiment, which shows that as the length of a side chain increases the Krafft point increases. In addition, carbon atoms on a branch of the hydrophobic chain have about half the effect of carbon atoms on a straight chain. The positive effect of the Randić index confirms this observation. The hydrophobic chain also has an effect on the solubility. Compared with alkyl sulfates with the same number of C atoms in the hydrophobic chain, the methyl ester sulfonates

have lower Krafft points. The higher solubility results from the greater hydrophilic tendency of the hydrophilic portion. The methyl ester group in the α -ester sulfonates can also be regarded as a short chain side group. The superiority of the model 2 over that of the model 1 may be due to the fact that this model considers both the molecular compactness and branching.

The presence of the reciprocal of dipole moment of the molecules as a descriptor in both models indicates that the polarity of the anionic surfactants as well as their topology plays a role in micelle formation. The calculated values of the descriptors from the selected models, along with the calculated values of Krafft point obtained using both models 1 and 2 together with the experimental values are given in Table 5. It can be seen from this table that as the length of the hydrophobic chain increases DIP^{-1} decreases and the Krafft point increases.

In order to test the validity of the selected models cross-validation and AIC procedures were used in this work. Tables 2 and 3 reveal the values of 0.863 and 0.883 for the cross-validated and 92.65 and 89.92 for the AIC of the models 1 and 2, respectively. This indicates the capability of both models in predicting the Krafft point for anionic surfactants. Although the statistics of the model 2 are slightly better than that of the model 1, model 1 has less descriptors. On the other hand, the descriptor VT^{-1} is collinear with DIP^{-1} and RA in model 2. Therefore, we believe that the model 1 is superior to the model 2.

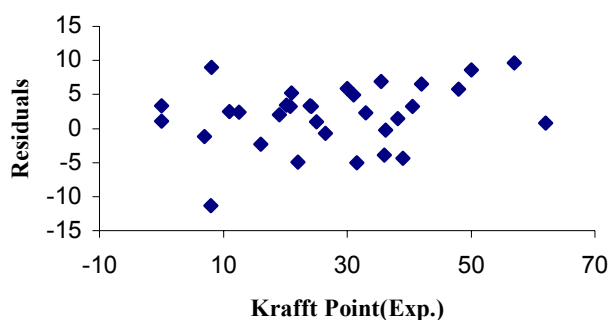


Figure 2. Plot of residuals *versus* experimental values for the Krafft point.

Figure 1 shows the plot of the calculated Krafft point obtained by using the model 1 *versus* the experimental values for the surfactants studied in this work. This line shows a high correlation coefficient ($r = 0.973$) and a low standard deviation ($s = 3.320$). The residuals of the MLR predicted values for the Krafft point are plotted against the experimental values in Figure 2. The propagation of residuals in both sides of zero indicates that no systematic error exists in the development of the MLR model.

4 CONCLUSIONS

From the results obtained in this work one may conclude that the topological characteristics such as compactness and branching of the anionic surfactants have a major role in micelle formation of these compounds and their Krafft temperature. The polarity of the molecules is also important in this respect but its effect is less than that of the topology of the surfactants. It can be concluded that the development of a linear equation between the Krafft point of the surfactants and the theoretical descriptors is of significant help in designing new surfactants.

5 REFERENCES

- [1] M. R. Porter, *Handbook of Surfactants* 2edn, Chapman & Hall, 1994, pp. 116–131.
- [2] H. W. Stache, *Anionic Surfactants, Organic Chemistry*, Vol 56, Marcel Dekker Inc, 1996, pp. 223–255.
- [3] C. Mesa and L. Coppola, Krafft Point Solubility Phenomena, *Colloids Surf.* **1989**, *35*, 325–328.
- [4] Y. Fang, The Relationships between Krafft Point and CMC and π_{\max} in Surface Tension Reduction, *Riyong Huaxue Gongye* **1991**, *1*, 20–24.
- [5] T. Gu and J. Sjoebloom, Empirical Relationships between the Krafft Points and the Structural Units in surfactants, *Acta Chem. Scand.* 1991, *45*, 762–765.
- [6] K. Tsujii, N. Saito, and T. Takeuchi, Krafft Points of Anionic Surfactants and their Mixtures with Special Attention to their Applicability in Hard Water, *J. Phys. Chem.* **1980**, *84*, 2287–2291.
- [7] SPSS/PC, The Statistical Package for IBM PC, Quaid Software, Ontario, 1986.
- [8] MOPAC Package, Version 6, U.S. Air Force Academy, Colorado Spring, CO. 80840.
- [9] HyperChem, Release 3 for Windows, 1993, Hypercube, Inc. and Autodesk, Inc; developed by Hypercube, Inc.
- [10] N. M. Van Os, J. R. Haak, and L. A. M. Rupert, *Physico–Chemical Properties of Selected Anionic, Cationic and Nonionic Surfactants*, Elsevier Scienc Publishers, 1993, pp. 9–80.
- [11] M. Randić, On Characterization of Molecular Branching, *J. Am. Chem. Soc.* **1975**, *97*, 6609–6615.
- [12] M. J. S. Dewar, E. G. Zoebisch, E. F. Healy, and J. J. P. Stewart, AM1: A New General Purpose Quantum Mechanical Molecular Model, *J. Am. Chem. Soc.* **1985**, *107*, 3902–3909.
- [13] T. R. Stouch and P. C. Jurs, A Simple Method for the Representation Quantification and Comparison of the Volumes and Shapes of Chemical Compounds, *J. Chem. Inf. Comput. Sci.* **1986**, *26*, 4–12.
- [14] M. Jalali–Heravi and E. Konouz, Use of Quantitative Structure Activity Relationships in Prediction of CMC of Nonionic Surfactants, *Quant. Struct.–Act. Relat.* **2000**, *19*, 135–141.
- [15] M. Jalali–Heravi and E. Konouz, Prediction of Critical Micelle Concentration of Some Anionic Surfactants Using Multiple Regression Techniques: A Quantitative Structure– Activity Relationship Study, *J. Surfactants Detergents* **2000**, *3*, 47–52.
- [16] S. Bohanec and M. Moder, A Computer Program for Searching the Best Model for Describing Different Experimental Systems, *Anal. Chim. Acta* **1997**, *340*, 267–275.