# Modeling Diamagnetic and Magnetooptic Properties of Organic Compounds with the TOSS-MODE Approach†

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The topological substructural molecular design (TOSS-MODE) approach is used to describe the diamagnetic susceptibility of organic compounds. Two data sets composed of 233 aliphatic and 85 aromatic compounds were studied for which good linear correlations were found. The contributions of many different structural fragments and atomic groups were computed by the current approach. The predictive ability of the models developed was tested by using external prediction sets of compounds of different classes than those used in training. A quantitative model based on the current approach was developed to compute the diamagnetic susceptibility exaltation of aromatic compounds, which is exemplified by the study of polycyclic aromatic hydrocarbons. The rotatory power of organic compounds in a magnetic field was also described by the TOSS-MODE approach. Good linear correlations were obtained for this property in aliphatic and aromatic compounds. The predictive abilities of the models found were tested by external prediction sets for which good correlations between calculated and experimental values are found.

## INTRODUCTION

The application of graph theoretical concepts for the description of chemical structures has evolved from the description of physical properties of alkanes by using relatively simple topological indices to the combined use of more potent descriptors to predict complex physicochemical and biological properties of structurally diverse data sets of organic compounds.[1] However, even today more than 70% of the papers published in the *Journal of Chemical Information and Computer Sciences* dealing with chemical graph theory are devoted to the study of hydrocarbons, which, as Milne has stated, constitute less than 3% of the topics of interest in a standard organic chemistry book.[2]

In the context of novel methods based on chemical graph theory developed for modeling physicochemical and biological properties, our group has introduced the TOSS-MODE approach.[3] The topological substructural molecular design approach (TOSS-MODE) has been applied to the description of physicochemical and biological properties of organic compounds.[3−9] It was also successfully applied to the virtual screening of novel anticancer compounds, which were then synthesized and evaluated on three different cellular lines.[10] Studies for the virtual screening and design of anticonvulsant compounds were also conducted with this theoretical approach.[11] Some other applications for the design of biologically active compounds have been reviewed in ref 3. TOSS-MODE has been extended to consider three-dimensional features of small/medium sized molecules as well as to proteins[12] based on the iterated line graph sequence approach.[13,14]

In the current work we continue by testing the possibilities of this approach for modeling and predicting properties of structurally diverse organic compounds. Here we will model the diamagnetic susceptibilities and the Faraday effect of large data sets of organic compounds.

The diamagnetic susceptibility $\chi$ of organic compounds is an important physicochemical property defined by the ratio of the intensity of magnetization produced in a substance ($M$) to the magnetizing force or intensity of field ($H$) to which it is subjected:[15−18]

$$\chi = M/H \tag{1}$$

This volume magnetic susceptibility is related to the more useful molar diamagnetic susceptibility $\chi_M$ by multiplying it by the molar volume $V_M$. A substance for which one has $\chi < 0$ is diamagnetic, and its molar diamagnetic susceptibility can be obtained from the Langevin−Pauli formula.[15−18]

There has been a continued interest in chemistry, based on the theoretical and practical importance of this property, for the determination and prediction of diamagnetic susceptibility of organic and organometallic compounds.[18] Recently, experimental and theoretical efforts in the field of diamagnetic susceptibility of organic compounds are devoted to the determination of this property by different ways in complex systems.[19−22]

The interest in theoretical treatments for magnetic susceptibility dates from the beginning of the twentieth century. The molecular susceptibility has been observed to be calculable from atomic contributions, and some additive

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models have appeared in the literature, such as Pascal's model,[23] which has been successful in the prediction of diamagnetic susceptibilities of organic compounds and is used even today.[18] A simple quantum chemical approach was developed by Hameka[24] to describe diamagnetic susceptibilities of several classes of organic compounds. In Hameka's approach not only atomic contributions are considered, but also contributions coming from bonds and bond−bond interactions are included. Recent studies include quantum chemical approaches such as the path-integral formulation of quantum mechanics, Weizsäcker energy of many-electron systems, and density-functional methods,[25−28] graph theoretical concepts,[29−31] or integrated molecular transform.[32] We have used the spectral moments of the bond matrix for describing the diamagnetic susceptibilities of alkanes and haloalkanes.[7]

A very important theoretical problem related to diamagnetic susceptibility is the aromaticity.[33−36] The values of $\chi_M$ have been used to calculate a "magnetic criterion" of aromaticity in organic and organometallic compounds. Aromaticity is one of the most important general concepts for the understanding of organic chemistry.[37,38] Along with several other aromaticity indices introduced in the literature, the importance of the diamagnetic susceptibility exaltation in defining this concept has been clearly recognized. Despite the controversy existing on the orthogonality or not of the "classical" and "magnetic" criteria of aromaticity,[39] it has been stated that, "Compounds which exhibit significantly exalted diamagnetic susceptibility are aromatic."[39d]

On the other hand, the rotation of the plane of polarization of light passing through transparent media in the direction of the lines of force of a strong magnetic field is called the Faraday effect.[18] The induced rotation of the plane of polarization is determined by the direction of the field. It also depends on the nature of the substance and it is proportional to the length of the path and to the intensity of the magnetic field:

$$\alpha = VlH_z \tag{2}$$

where $\alpha$ is the induced rotation of the plane of polarization, $l$ is the path length, $H_z$ is the magnetic field in the direction of propagation of light, and $V$ is the Verdet constant, which is material specific and a function of the frequency.

The Faraday effect is also called the magnetooptic rotation. Today, it can be understood as an appearance of optical activity in the medium; that is, its refractive indices for right and left circularly polarized light had become unequal due to the application of the magnetic field, left- and right-handed motions about a magnetic field being nonequivalent.[40]

The molar magnetic rotation [MMR] was defined by Perkins when studying the magnetic rotation of organic substances by using sodium light. He compares the rotatory power of substances with that of water, for which [MMR] is defined as

$$[M] = \frac{MV\alpha}{MV'\alpha'} \tag{3}$$

where $\alpha$ is the angle of induced rotation of the plane of polarization and MV is the molar volume of the liquid; $\alpha'$ and MV′ are the same magnitudes for water.[40]

**Table 1.** Composition of the Data Set of Aliphatic Compounds

| chemical family | number | nonsubstituted | substituted |
|---|---|---|---|
| hydrocarbons[a] | 61 | | |
| non-hydrocarbons[b] | 172 | | |
| carboxylic acids | 10 | 7 | 3 |
| alcohols | 23 | 18 | 5 |
| aldehydes | 3 | 3 | 0 |
| anhydrides | 1 | 1 | 0 |
| ketones | 23 | 21 | 2 |
| amines | 17 | 16 | 1 |
| halides | 69 | 49 | 20 |
| ethers | 13 | 3 | 10 |
| esters | 25 | 17 | 8 |
| acid halides | 1 | 1 | 0 |
| amides | 2 | 2 | 0 |
| nitro compounds | 4 | 3 | 1 |
| nitriles | 5 | 5 | 0 |
| nitrates | 1 | 1 | 0 |
| sulfides | 3 | 3 | 0 |
| thiocyanates | 2 | 2 | 0 |

[a] Alkanes and cycloalkanes; alkenes and cycloalkenes; alkynes. [b] Nonhydrocarbons are divided into the following groups.

Magnetooptic rotation is today a standard investigative tool for condensed matter science. The Faraday effect has found an important use in communications as a means of modulating the polarization properties of light beams, allowing the information of the transmitted light to be greatly increased.[41]

## THEORETICAL APPROACH

Our theoretical approach is based on the assumption that the diamagnetic susceptibility and the magnetooptic rotation of organic molecules can be expressed in terms of the spectral moments of the topological bond matrix of such molecules in the following way:[3]

$$-\chi_M \times 10^{-6}\,(\text{cgs}) = a_0 + a_1\mu_1 + a_2\mu_2 + a_3\mu_3 + a_4\mu_4 + \ldots + a_n\mu_n \tag{4}$$

$$[\text{MMR}] = a_0 + a_1\mu_1 + a_2\mu_2 + a_3\mu_3 + a_4\mu_4 + \ldots + a_n\mu_n \tag{5}$$

The topological bond matrix has been previously defined and studied in the chemical context,[42,43] and it has been rediscovered as a source of molecular descriptors for structure−property studies.[44−50]

Here, we will consider standard bond distances in the diagonal entries of the bond matrix.[5] The spectral moments derived from it can be expressed in terms of the different molecular fragments present in the chemical structures of organic molecules.[3−9] By using these expressions the diamagnetic susceptibility and the molar magnetic rotation can be expressed as additive functions of the different fragments present in molecular structures taking the following form:

$$-\chi_M \times 10^{-6}\,(\text{cgs}) = a_0 + a_1'|F_1| + a_2'|F|_2 + a_3'|F_3| + \cdots + a_n'|F_n| \tag{6}$$

$$[M] = a_0 + a_1'|F_1| + a_2'|F|_2 + a_3'|F_3| + \cdots + a_n'|F_n| \tag{7}$$

where $a_i'$ represent the modified coefficients accounting for the contribution of the different fragments $F_i$ (the vertical brackets represent the number of such fragments). The

**Table 2.** Observed and Calculated Diamagnetic Susceptibilities of Aliphatic Organic Compounds; Residuals of the Regression and from Cross-Validation

| compound | $-\chi_M$ ($10^{-6}$ cgs) obsd | $-\chi_M$ ($10^{-6}$ cgs) calcd | residual regress. | residual cross-val. |
|---|---|---|---|---|
| acetaldehyde | 22.7 | 28.17 | −5.47 | −5.58 |
| acetamide | 34.1 | 33.01 | 1.09 | 1.11 |
| acetic acid | 31.54 | 34.35 | −2.81 | −2.86 |
| acetic anhydride | 52.8 | 48.81 | 3.99 | 4.12 |
| acetone | 33.7 | 39.44 | −5.73 | −5.82 |
| acetylene | 12.5 | 16.88 | −4.38 | −4.49 |
| *n*-amyl alcohol | 67.5 | 70.86 | −3.36 | −3.41 |
| isoamyl alcohol | 68.96 | 70.31 | −1.35 | −1.36 |
| *tert*-amyl alcohol | 70.9 | 66.85 | 4.05 | 4.13 |
| n-amylamine | 69.4 | 71.96 | −2.56 | −2.59 |
| isoamylamine | 71.6 | 71.40 | 0.20 | 0.20 |
| isoamyl bromide | 88.7 | 82.95 | 5.75 | 5.84 |
| isoamyl chloride | 79 | 78.77 | 0.23 | 0.23 |
| bromochloromethane | 55 | 52.82 | 2.18 | 2.24 |
| bromodichloromethane | 66.3 | 73.69 | −7.39 | −7.64 |
| bromotrichloromethane | 73.1 | 89.61 | −16.51 | −17.15 |
| butane | 57.4 | 49.79 | 7.61 | 7.70 |
| isobutane | 51.7 | 50.98 | 0.72 | 0.73 |
| *n*-butyl alcohol | 56.536 | 58.85 | −2.31 | −2.34 |
| isobutyl alcohol | 57.704 | 58.29 | −0.59 | −0.59 |
| *sec*-butyl alcohol | 57.683 | 57.90 | −0.22 | −0.22 |
| *tert*-butyl alcohol | 57.42 | 58.32 | −0.90 | −0.93 |
| *n*-butylamine | 58.9 | 59.94 | −1.04 | −1.06 |
| isobutylamine | 59.8 | 59.39 | 0.42 | 0.42 |
| isobutyl bromide | 79.88 | 70.93 | 8.94 | 9.08 |
| *n*-butyl chloride | 67.1 | 67.32 | −0.22 | −0.22 |
| carbon tetrachloride | 66.6 | 85.43 | −18.83 | −19.47 |
| carbon tetrabromide | 93.73 | 101.79 | −8.06 | −8.62 |
| chloroacetic acid | 48.1 | 49.99 | −1.89 | −1.91 |
| chloroacetone | 50.9 | 55.08 | −4.18 | −4.21 |
| chlorodibromomethane | 75.1 | 78.09 | −2.99 | −3.12 |
| chlorodifluoromethane | 38.6 | 48.62 | −10.02 | −10.16 |
| 1-chloro-2,3-dihydroxypropane | 77.9 | 70.72 | 7.18 | 7.21 |
| chlorotrifluoromethane | 45.3 | 54.84 | −9.54 | −9.84 |
| cyclohexane | 68.13 | 73.27 | −5.14 | −5.26 |
| 1,3-cyclohexadiene | 48.6 | 55.29 | −6.68 | −6.95 |
| 1,4-cyclohexadiene | 48.7 | 56.69 | −7.99 | −8.29 |
| cyclohexanol | 73.4 | 79.63 | −6.23 | −6.38 |
| cyclohexanone | 62 | 71.16 | −9.16 | −9.44 |
| cyclohexene | 57.5 | 64.98 | −7.48 | −7.69 |
| cyclooctane | 91.4 | 97.29 | −5.89 | −6.03 |
| cyclooctene | 84.6 | 89.01 | −4.41 | −4.52 |
| cyclopentane | 59.18 | 61.25 | −2.07 | −2.13 |
| cyclopentanone | 51.63 | 59.14 | −7.51 | −7.79 |
| cyclopropane | 39.9 | 50.98 | −11.08 | −11.23 |
| dibromodichloromethane | 81.1 | 93.73 | −12.63 | −13.20 |
| 1,2-dibromo-2-fluoroethane | 78 | 77.50 | 0.50 | 0.51 |
| 1,2-dibromotetrachloroethane | 126 | 128.01 | −2.01 | −2.34 |
| 1,1-dichlorodifluoroethylene | 60 | 59.96 | 0.04 | 0.04 |
| 1,2-dichloro-1,2-dibromoethane | 108.6 | 104.52 | 4.08 | 4.31 |
| dichlorodifluoromethane | 52.2 | 65.27 | −13.06 | −13.40 |
| 1,1-dichloroethylene | 49.2 | 55.54 | −6.34 | −6.44 |
| 1,2-chloro-2-hydroxypropane | 80.1 | 78.46 | 1.64 | 1.66 |
| dicyclohexyl | 129.31 | 134.96 | −5.65 | −6.45 |
| diethylamine | 56.8 | 57.09 | −0.29 | −0.29 |
| diethylcyclohexylamine | 124.5 | 115.43 | 9.07 | 9.56 |
| 1,1-difluoro-2,2-dibromoethane | 85.5 | 83.58 | 1.92 | 1.97 |
| 1,1-difluoro-2,2-dichloroethylamyl ether | 129.84 | 130.36 | −0.51 | −0.53 |
| 1,1-difluoro-2,2-dichloroethylbutyl ether | 119.48 | 118.34 | 1.14 | 1.18 |
| 1,1-difluoro-2,2-dichloroethylpropyl ether | 107.19 | 106.33 | 0.86 | 0.89 |
| 1,1-difluoro-2,2-dichloroethylethyl ether | 96.13 | 94.31 | 1.82 | 1.87 |
| 1,1-difluoro-2,2-dichloroethylethyl ether | 80.68 | 83.09 | −2.40 | −2.48 |
| di-*n*-heptylamine | 171.5 | 177.23 | −5.73 | −6.50 |
| di-*n*-hexylamine | 148.9 | 153.20 | −4.30 | −4.67 |
| dimethoxymethane | 47.3 | 48.36 | −1.06 | −1.07 |
| 2,2-dimethylbutane | 76.24 | 70.21 | 6.03 | 6.14 |
| 2,3-dimethylbutane | 76.22 | 70.96 | 5.26 | 5.32 |
| 2,4-dimethyl-2,4-hexadiene | 78.7 | 74.23 | 4.47 | 4.52 |
| 2,5-dimethyl-4-heptene | 100.6 | 97.30 | 3.30 | 3.34 |
| 2,3-dimethylhexane | 98.77 | 93.25 | 5.52 | 5.57 |
| 2,5-dimethylhexane | 98.15 | 96.73 | 1.42 | 1.45 |

**Table 2** (Continued)

| compound | $-\chi_M$ ($10^{-6}$ cgs) obsd | calcd | residual regress. | cross-val. |
|---|---|---|---|---|
| 3,4-dimethylhexane | 99.06 | 91.50 | 7.56 | 7.60 |
| 2,6-dimethyl-4-hexanol | 116.9 | 103.65 | 13.25 | 13.48 |
| 2,4-dimethylnonane | 134.68 | 131.03 | 3.65 | 3.77 |
| 3,4-dimethylnonane | 134.7 | 127.54 | 7.16 | 7.31 |
| 4,5-dimethylnonane | 134.52 | 127.54 | 6.98 | 7.12 |
| 2,6-dimethyloctane | 122.54 | 119.02 | 3.52 | 3.61 |
| 2,2-dimethylpentane | 86.97 | 82.22 | 4.75 | 4.83 |
| 2,3-dimethylpentane | 87.51 | 81.23 | 6.28 | 6.32 |
| 2,4-dimethylpentane | 87.48 | 84.72 | 2.76 | 2.81 |
| 2,2-dimethylpropane | 63.1 | 61.68 | 1.42 | 1.45 |
| ethane | 27.3 | 24.02 | 3.28 | 3.36 |
| ethyl alcohol | 33.6 | 34.82 | −1.22 | −1.24 |
| ethyl bromide | 54.7 | 47.47 | 7.23 | 7.38 |
| ethyl bromoacetate | 82.8 | 71.40 | 11.40 | 11.48 |
| ethyl *n*-butyrate | 77.7 | 73.71 | 3.99 | 4.03 |
| ethyl isobutyrate | 78.32 | 71.34 | 6.98 | 7.06 |
| ethyl chloroacetate | 72.3 | 67.21 | 5.09 | 5.12 |
| ethyl cyclohexane | 91.09 | 93.25 | −2.16 | −2.21 |
| ethyl dichloroacetate | 85.2 | 83.61 | 1.59 | 1.60 |
| ethyl iodide | 69.7 | 51.63 | 18.07 | 18.59 |
| ethyl propionate | 66.5 | 61.70 | 4.80 | 4.86 |
| ethyl tribromoacetate | 119.5 | 109.10 | 10.40 | 10.96 |
| ethyl trichloroacetate | 99.6 | 96.52 | 3.08 | 3.19 |
| fluorobromoacetic acid | 59.5 | 60.69 | −1.19 | −1.20 |
| fluorodichloromethane | 48.8 | 59.04 | −10.24 | −10.42 |
| formic acid | 19.9 | 23.69 | −3.79 | −3.87 |
| formamide | 21.9 | 22.51 | −0.61 | −0.62 |
| 1,2-heptadiene | 73.5 | 70.66 | 2.84 | 2.90 |
| 2,3-heptadiene | 72.1 | 65.68 | 6.42 | 6.57 |
| heptaldehyde | 81.02 | 88.10 | −7.08 | −7.24 |
| heptane | 85.24 | 85.84 | −0.59 | −0.60 |
| 4-heptanol | 91.5 | 92.20 | −0.70 | −0.70 |
| *n*-heptanoic acid | 88.6 | 92.53 | −3.93 | −3.99 |
| *n*-heptylamine | 93.1 | 95.98 | −2.88 | −2.95 |
| heptylcyclohexane | 147.4 | 153.32 | −5.92 | −6.22 |
| 1-heptyne | 77 | 73.40 | 3.60 | 3.66 |
| 2-heptyne | 79.5 | 68.68 | 10.82 | 11.05 |
| hexabromoethane | 148 | 144.65 | 3.35 | 4.30 |
| hexachloroethane | 112.7 | 119.53 | −6.83 | −7.69 |
| *n*-hexane | 74.6 | 73.82 | 0.78 | 0.78 |
| *n*-hexyl alcohol | 79.2 | 82.88 | −3.68 | −3.73 |
| 4-hydroxy-2-butanone | 48.5 | 58.62 | −10.12 | −10.20 |
| methyl acetate | 42.6 | 40.33 | 2.27 | 2.30 |
| methyl alcohol | 21.4 | 21.84 | −0.44 | −0.45 |
| methyl bromide | 42.8 | 31.24 | 11.56 | 12.04 |
| methylamine | 27 | 22.65 | 4.35 | 4.46 |
| 2-methylbutane | 64.4 | 61.25 | 3.15 | 3.17 |
| 2-methyl-2-butene | 54.14 | 53.66 | 0.48 | 0.48 |
| methyl chloride | 32 | 28.10 | 3.90 | 4.02 |
| methyl chloroacetate | 58.1 | 55.98 | 2.12 | 2.14 |
| methylcyclohexane | 78.91 | 82.98 | −4.07 | −4.17 |
| 2-methylcyclohexanone | 74 | 79.06 | −5.06 | −5.28 |
| 3-methylcyclohexanone | 74.8 | 80.87 | −6.07 | −6.32 |
| methylcyclopentane | 70.17 | 70.97 | −0.80 | −0.81 |
| methyl dichloroacetate | 73.1 | 72.38 | 0.72 | 0.73 |
| 3-methylheptane | 97.99 | 95.55 | 2.44 | 2.46 |
| 2-methylheptene | 88 | 89.01 | −1.00 | −1.01 |
| 5-methyl-1,2-hexadiene | 73.6 | 70.10 | 3.50 | 3.53 |
| 2-methylhexane | 86.24 | 85.28 | 0.96 | 0.97 |
| 5-methyl-5-nonene | 111.6 | 109.87 | 1.73 | 1.76 |
| 4-methyloctane | 109.63 | 107.56 | 2.07 | 2.10 |
| 2-methylpentane | 75.26 | 73.26 | 2.00 | 2.01 |
| 3-methylpentane | 75.52 | 71.52 | 4.00 | 4.02 |
| 4-methyl-2-pentanol | 80.4 | 81.37 | −0.97 | −0.98 |
| 2-methylpropene | 44.4 | 43.53 | 0.87 | 0.88 |
| methyl propionate | 55 | 50.46 | 4.54 | 4.59 |
| nitroethane | 35.4 | 39.16 | −3.76 | −3.81 |
| nitromethane | 21.1 | 29.38 | −8.28 | −8.45 |
| 2-nitropropane | 45.73 | 48.62 | −2.89 | −2.95 |
| *n*-nonane | 108.13 | 109.86 | −1.73 | −1.78 |
| *n*-octane | 96.63 | 97.85 | −1.22 | −1.24 |
| octyl alcohol | 102.65 | 106.90 | −4.25 | −4.38 |

**Table 2** (Continued)

| compound | $-\chi_M$ ($10^{-6}$ cgs) obsd | $-\chi_M$ ($10^{-6}$ cgs) calcd | residual regress. | residual cross-val. |
|---|---|---|---|---|
| octyl chloride | 114.9 | 115.37 | −0.47 | −0.48 |
| octylcyclohexane | 158.09 | 165.33 | −7.24 | −7.70 |
| pentachloroethane | 99.1 | 108.37 | −9.27 | −9.64 |
| 2,3-pentadiene | 49.1 | 41.79 | 7.31 | 7.48 |
| *n*-pentane | 63.05 | 61.81 | 1.24 | 1.25 |
| 2,4-pentanediol | 70.4 | 78.02 | −7.62 | −7.77 |
| propane | 40.5 | 37.78 | 2.72 | 2.76 |
| propene | 31.5 | 31.75 | −0.25 | −0.25 |
| propionaldehyde | 34.32 | 40.05 | −5.73 | −5.81 |
| propionic acid | 43.5 | 44.48 | −0.98 | −0.98 |
| propionitrile | 38.5 | 36.10 | 2.40 | 2.44 |
| *n*-propyl acetate | 65.91 | 63.58 | 2.33 | 2.35 |
| isopropyl acetate | 67.04 | 62.63 | 4.41 | 4.49 |
| *n*-propyl alcohol | 45.176 | 46.84 | −1.66 | −1.68 |
| isopropyl alcohol | 45.794 | 47.63 | −1.83 | −1.86 |
| isopropyl bromide | 65.1 | 61.74 | 3.36 | 3.42 |
| *n*-propyl bromide | 65.6 | 59.48 | 6.12 | 6.23 |
| isopropylcyclohexane | 102.65 | 102.96 | −0.31 | −0.32 |
| acetonitrile | 28 | 24.65 | 3.35 | 3.42 |
| acetyl chloride | 38.9 | 45.52 | −6.62 | −6.71 |
| alanine | 50.5 | 52.01 | −1.51 | −1.53 |
| allyl acetate | 56.7 | 57.41 | −0.71 | −0.71 |
| allyl alcohol | 36.7 | 40.66 | −3.96 | −4.02 |
| *n*-amyl acetate | 89.06 | 87.61 | 1.45 | 1.47 |
| isoamyl acetate | 89.4 | 87.05 | 2.35 | 2.39 |
| isoamyl *n*-butyrate | 113.52 | 109.19 | 4.32 | 4.43 |
| isoamyl cyanide | 73.4 | 71.58 | 1.82 | 1.83 |
| isoamyl ether | 129 | 123.36 | 5.64 | 5.84 |
| n-amyl methyl ketone | 80.5 | 85.61 | −5.11 | −5.16 |
| isoamyl propionate | 101.73 | 97.18 | 4.55 | 4.63 |
| bromoform | 82.6 | 82.44 | 0.16 | 0.17 |
| *n*-butyl acetate | 77.47 | 75.59 | 1.88 | 1.89 |
| isobutyl acetate | 78.52 | 75.04 | 3.48 | 3.54 |
| 2-*n*-butyl chloride | 67.4 | 67.42 | −0.02 | −0.02 |
| *n*-butyl cyanide | 62.8 | 60.13 | 2.67 | 2.71 |
| *tert*-butylcyclohexane | 115.09 | 110.18 | 4.91 | 5.14 |
| *n*-butyl ethyl ketone | 80.73 | 83.73 | −3.00 | −3.02 |
| *n*-butyl formate | 65.83 | 66.69 | −0.85 | −0.86 |
| isobutyl formate | 66.79 | 66.12 | 0.67 | 0.67 |
| isobutyl methyl ketone | 70.05 | 73.04 | −2.99 | −3.04 |
| *tert*-butyl methyl ketone | 69.86 | 66.43 | 3.43 | 3.54 |
| *n*-butyric acid | 55.1 | 56.49 | −1.39 | −1.40 |
| isobutyric acid | 56.06 | 54.12 | 1.94 | 1.97 |
| butyronitrile | 49.4 | 48.11 | 1.28 | 1.30 |
| chloroform | 59.3 | 69.24 | −9.94 | −10.20 |
| cyclohexanecarboxylic acid | 83.24 | 86.12 | −2.88 | −3.01 |
| cyclooctatetraene | 53.9 | 58.51 | −4.61 | −4.96 |
| diisoamylamine | 133.1 | 126.13 | 6.97 | 7.23 |
| di-*n*-butylamine | 103.7 | 105.14 | −1.44 | −1.48 |
| diisobutylamine | 105.7 | 104.03 | 1.67 | 1.71 |
| di-*sec*-butylamine | 105.9 | 100.05 | 5.85 | 5.90 |
| diisobutyl ketone | 104.3 | 106.64 | −2.34 | −2.43 |
| *n*-amyl nitrate | 76.4 | 75.20 | 1.20 | 1.21 |
| *n*-butyl bromide | 77.14 | 71.49 | 5.64 | 5.74 |
| *n*-butyl iodide | 93.6 | 75.66 | 17.94 | 18.36 |
| *n*-butyl sulfide | 113.7 | 126.58 | −12.89 | −13.48 |
| *n*-butyl thiocyanate | 79.38 | 85.79 | −6.41 | −6.51 |
| di-*tert*-butyl ketone | 104.06 | 93.42 | 10.64 | 11.86 |
| 1,1-dicyclohexylnonane | 231.98 | 237.29 | −5.31 | −6.76 |
| diethyl ketone | 58.1 | 59.70 | −1.60 | −1.60 |
| diethyl sulfide | 67.9 | 78.53 | −10.63 | −10.85 |
| dimethyl sulfide | 44.9 | 51.04 | −6.14 | −6.30 |
| 1,4-dioxane | 52.16 | 58.28 | −6.12 | −6.33 |
| di-*n*-propyl ketone | 80.45 | 83.72 | −3.28 | −3.30 |
| diisopropyl ketone | 81.14 | 78.99 | 2.15 | 2.19 |
| diethyl ether | 55.1 | 54.31 | 0.78 | 0.79 |
| ethyl formate | 43 | 42.65 | 0.35 | 0.35 |
| ethyl *n*-propyl ketone | 69.03 | 71.71 | −2.68 | −2.69 |
| ethyl thiocyanate | 55.7 | 64.74 | −9.04 | −9.13 |
| *n*-hexyl methyl ketone | 91.4 | 97.62 | −6.23 | −6.31 |
| methyl butyl ketone | 69.1 | 73.59 | −4.49 | −4.52 |
| dimethyl ether | 26.3 | 31.84 | −5.54 | −5.63 |

**Table 2** (Continued)

| compound | $-\chi_M$ ($10^{-6}$ cgs) obsd | $-\chi_M$ ($10^{-6}$ cgs) calcd | residual regress. | residual cross-val. |
|---|---|---|---|---|
| *n*-methyl ethyl ketone | 45.5 | 49.57 | −4.07 | −4.10 |
| methyl *n*-propyl ketone | 57.41 | 61.58 | −4.17 | −4.19 |
| methyl isopropyl ketone | 58.45 | 59.21 | −0.76 | −0.77 |
| *n*-propyl iodide | 84.3 | 63.64 | 20.66 | 21.17 |
| 1,1,2,2-tetrabromoethane | 123.4 | 113.46 | 9.94 | 10.80 |
| 1,1,2,2-tetrachloroethane | 89.8 | 95.47 | −5.67 | −5.88 |
| 1,2,3-tribromopropane | 117.9 | 101.66 | 16.24 | 17.15 |
| trichloronitromethane | 75.3 | 73.86 | 1.44 | 1.48 |
| triethylamine | 81.4 | 73.96 | 7.44 | 7.49 |
| 2,2,3-trimethylbutane | 88.36 | 78.18 | 10.18 | 10.44 |
| 2,2,3-trimethylpentane | 99.86 | 88.45 | 11.41 | 11.68 |
| 1,2-dichloro-1,1,2-trifluoroethane | 66.2 | 77.60 | −11.40 | −11.68 |
| 1,2-dibromo-1,1,2-trifluoroethane | 90.9 | 86.70 | 4.19 | 4.29 |
| 1-methoxy-1,1,2-trifluoroethane | 55.9 | 59.09 | −3.20 | −3.29 |
| 1-chloro-2-propene | 47.8 | 49.14 | −1.34 | −1.35 |
| 1-bromo-2-propene | 58.6 | 53.33 | 5.27 | 5.34 |
| 1-iodo-2-propene | 72.8 | 57.50 | 15.30 | 15.58 |
| 1-amine-2-propene | 40.1 | 41.76 | −1.66 | −1.68 |

procedure permitting transformation of models 4 and 5 to models 6 and 7 has been detailed elsewhere.[3−9] A summary of this procedure is given in the Appendix.

To find expressions of the type of eq 4 we have selected two series of organic compounds for which the experimental values of diamagnetic susceptibilities are reported in the literature:[51] 233 aliphatic organic compounds formed the first series and 85 aromatic compounds the second one. The composition of the data set of aliphatic compounds is illustrated in Table 1, showing that only 25% of these compounds are hydrocarbons. The series of aromatic compounds also show a great structural variability. Both series of compounds are given in Tables 2 and 3, respectively.

The data sets used for the development of the models of type 5 are composed of 65 aliphatic and 35 aromatic compounds. The division of the data sets into aliphatic and aromatic compounds was necessary due to the exaltation that this property, as well as the diamagnetic susceptibility, shows for the aromatic compounds. Of the aliphatic compounds only 18 are hydrocarbons, which represent 28% of the whole data set of aliphatic compounds. The data set of aromatic compounds is made mainly of substituted benzene compounds, but some heterocyclic compounds are also included. Very few values of the magnetooptic rotation of polycyclic aromatic compounds are reported in the literature.

## DESCRIPTION OF DIAMAGNETIC SUSCEPTIBILITY OF ORGANIC COMPOUNDS

The equations that relate the spectral moments to the diamagnetic susceptibilities of molecules were obtained by linear regression analysis, using the first 15 moments of the bond matrix as independent variables. The best linear fit between the spectral moments and the susceptibilities of aliphatic compounds is illustrated by

$$-\chi_M \times 10^{-6}\,(\text{cgs}) = 1.270 - 27.582\mu_0 + 54.546\mu_1 - 20.737\mu_2 + 4.927\mu_3 - 0.431\mu_4 \quad (8)$$

This model was obtained by using 233 aliphatic compounds as a training series. The correlation coefficient ($R$) of the fit is 0.980, and the standard deviation of the regression ($s$) is 6.06 cgs. The mean square error for the cross-validation in this data set is 6.18 cgs, which proves the predictive ability of this model. The best linear fit obtained to describe the susceptibilities of aromatic compounds is

$$-\chi_M \times 10^{-6}\,(\text{cgs}) = 19.592 - 51.0.25\mu_0 + 31.371\mu_1 + 10.530\mu_2 - 3.893\mu_3 + 0.445\mu_4 \quad (9)$$

The correlation coefficient here is $R = 0.980$, the standard deviation of the regression is 3.82 cgs, and the mean error in the cross-validation is 4.12 cgs. Experimental values, calculated values, residuals, and cross-validation residuals for both aliphatic and aromatic compounds are given in Table 2 and Table 3, respectively.

One of the most desirable attributes of the quantitative models developed to describe any physicochemical property is its predictive capacity. With the objective of validating models 8 and 9 for their predictive abilities, we selected a series of 20 aliphatic and 20 aromatic compounds. These compounds were never used in the development of these quantitative models, and they were selected from the original pool of chemicals for which the experimental values of $-\chi_M$ are known.[51] The experimental and calculated values of the diamagnetic susceptibilities for these compounds are given in Table 4.

These external prediction sets include amino acids, phosphates, sulfates, barbituric acid, carbohydrates, heterocycles, and polycyclic aromatic compounds. Despite this degree of difficulty the root of the mean square errors in both prediction series, i.e., aliphatic and aromatic compounds, were 8.49 and 4.00, respectively. The quadratic error in the prediction set of aromatic compounds is only 4.5% higher than that of the training series, while for the aliphatic compounds this value is increased by almost 29%. The greatest errors in this data set are recorded for some of the polyhalogenated compounds and for cholesterol. The error of 27.35 cgs obtained for cholesterol is understood for the noninclusion of any bi- or polycyclic aliphatic compound in the training series used in the present study.

For the polyhalogenated compounds given in the prediction set, the present method shows an overestimation of the diamagnetic susceptibility (see Table 4). This overestimation

**Table 3.** Observed and Calculated Diamagnetic Susceptibilities of Aromatic Organic Compounds; Residuals of the Regression and from Cross-Validation

| compound | $-\chi_M$ ($10^{-6}$ cgs) obsd | calcd | residual regress. | cross-val. |
|---|---|---|---|---|
| benzene | 54.84 | 56.00 | −1.16 | −1.26 |
| fluorobenzene | 58.4 | 57.50 | 0.90 | 0.94 |
| phenol | 60.21 | 59.01 | 1.20 | 1.26 |
| benzaldehyde | 60.78 | 63.79 | −3.01 | −3.14 |
| nitrobenzene | 61.8 | 63.59 | −1.79 | −1.83 |
| aniline | 62.95 | 63.58 | −0.63 | −0.66 |
| benzonitrile | 65.19 | 56.22 | 8.97 | 9.66 |
| *p*-nitrosonitrobenzene | 65.8 | 67.05 | −1.26 | −1.31 |
| *m*-nitrosonitrobenzene | 66 | 67.06 | −1.06 | −1.10 |
| toluene | 66.11 | 65.13 | 0.98 | 1.02 |
| *p*-nitroaniline | 66.43 | 71.17 | −4.74 | −4.89 |
| *o*-nitroaniline | 66.47 | 72.95 | −6.48 | −6.64 |
| *p*-nitrobenzaldehyde | 66.57 | 71.38 | −4.81 | −4.98 |
| phenylhydrazine | 67.82 | 67.36 | 0.46 | 0.48 |
| phenylhydroxylamine | 68.2 | 70.07 | −1.87 | −1.94 |
| *o*-nitrobenzaldehyde | 68.23 | 73.16 | −4.93 | −5.16 |
| *m*-nitrobenzaldehyde | 68.55 | 71.38 | −2.83 | −2.93 |
| *p*-nitrophenol | 69.5 | 66.59 | 2.90 | 3.02 |
| chlorobenzene | 69.97 | 72.56 | −2.59 | −2.67 |
| *m*-nitroaniline | 70.09 | 71.17 | −1.08 | −1.12 |
| benzoic acid | 70.28 | 66.95 | 3.33 | 3.40 |
| *m*-nitrophenol | 70.8 | 66.59 | 4.20 | 4.37 |
| phenylthiol | 70.8 | 76.53 | −5.73 | −5.92 |
| benzyl alcohol | 71.83 | 73.66 | −1.83 | −1.90 |
| acetophenone | 72.05 | 73.04 | −0.99 | −1.00 |
| *p*-toluidine | 72.1 | 72.71 | −0.61 | −0.63 |
| benzamide | 72.3 | 68.83 | 3.47 | 3.54 |
| 2,4-dinitrophenol | 73.1 | 75.96 | −2.86 | −3.14 |
| *o*-nitrophenol | 73.3 | 68.38 | 4.92 | 5.09 |
| 1,3,5-trinitrobenzene | 74.55 | 78.76 | −4.21 | −5.18 |
| *m*-toluidine | 74.6 | 72.71 | 1.89 | 1.95 |
| benzylamine | 75.26 | 75.22 | 0.04 | 0.04 |
| benzoyl chloride | 75.6 | 83.59 | −7.99 | −8.11 |
| *o*-methoxybenzaldehyde | 76 | 77.76 | −1.76 | −1.88 |
| *o*-toluidine | 76 | 74.49 | 1.51 | 1.55 |
| *o*-nitrobenzoic acid | 76.11 | 76.32 | −0.21 | −0.22 |
| *m*-xylene | 76.56 | 74.25 | 2.31 | 2.38 |
| *p*-xylene | 76.78 | 74.25 | 2.53 | 2.61 |
| *o*-aminobenzoic acid | 77.18 | 76.31 | 0.87 | 0.88 |
| ethylbenzene | 77.2 | 77.96 | −0.76 | −0.78 |
| *o*-chlorophenol | 77.4 | 77.34 | 0.05 | 0.06 |
| *p*-chlorophenol | 77.6 | 75.56 | 2.04 | 2.10 |
| *o*-xylene | 77.68 | 76.03 | 1.65 | 1.69 |
| *p*-methoxybenzaldehyde | 78 | 75.97 | 2.03 | 2.10 |
| *p*-nitrobenzoic acid | 78.81 | 74.54 | 4.27 | 4.54 |
| bromobenzene | 78.92 | 79.73 | −0.81 | −0.84 |
| *m*-anisidine | 79.95 | 75.77 | 4.18 | 4.24 |
| *m*-chlorotoluene | 80.07 | 81.68 | −1.61 | −1.67 |
| *p*-chlorotoluene | 80.07 | 81.68 | −1.61 | −1.67 |
| *m*-nitrobenzoic acid | 80.22 | 74.54 | 5.68 | 6.04 |
| *o*-anisidine | 80.44 | 77.55 | 2.89 | 2.98 |
| *p*-anisidine | 80.56 | 75.77 | 4.79 | 4.86 |
| phenyl isothiocyanate | 81.5 | 89.36 | −7.86 | −8.74 |
| benzyl chloride | 81.98 | 86.59 | −4.61 | −4.77 |
| *o*-chlorotoluene | 81.98 | 83.46 | −1.48 | −1.52 |
| *p*-dichlorobenzene | 82.93 | 89.11 | −6.18 | −6.45 |
| *m*-dichlorobenzene | 83.19 | 89.11 | −5.92 | −6.18 |
| *o*-chlorobenzoic acid | 83.56 | 85.29 | −1.73 | −1.76 |
| *p*-bromoaniline | 84.06 | 87.31 | −3.25 | −3.38 |
| *o*-dichlorobenzene | 84.26 | 90.90 | −6.64 | −6.84 |
| picric acid | 84.38 | 85.33 | −0.95 | −1.20 |
| *m*-bromoaniline | 84.89 | 87.31 | −2.42 | −2.52 |
| *p*-dimethoxybenzene | 86.65 | 80.37 | 6.28 | 6.47 |
| *m*-dimethoxybenzene | 87.21 | 80.37 | 6.84 | 7.05 |
| *o*-bromonitrobenzene | 87.3 | 89.10 | −1.80 | −1.83 |
| *o*-bromoaniline | 87.32 | 89.09 | −1.77 | −1.83 |
| *o*-dimethoxybenzene | 87.39 | 82.15 | 5.24 | 5.60 |
| *m*-bromonitrobenzene | 89.5 | 87.32 | 2.18 | 2.24 |
| *p*-bromonitrobenzene | 89.6 | 87.32 | 2.28 | 2.35 |
| iodobenzene | 92 | 88.22 | 3.77 | 3.95 |
| benzyl acetate | 93.18 | 84.90 | 8.28 | 9.43 |

**Table 3** (Continued)

| compound | $-\chi_M$ ($10^{-6}$ cgs) obsd | $-\chi_M$ ($10^{-6}$ cgs) calcd | residual regress. | residual cross-val. |
|---|---|---|---|---|
| *m*-bromotoluene | 93.4 | 88.85 | 4.54 | 4.73 |
| *n*-butylbenzene | 100.79 | 99.92 | 0.87 | 1.02 |
| *p*-iodotoluene | 101.31 | 97.35 | 3.96 | 4.19 |
| *p*-dibromobenzene | 101.4 | 103.46 | −2.06 | −2.21 |
| isobutylbenzene | 101.81 | 97.02 | 4.79 | 5.60 |
| *tert*-butylbenzene | 102.5 | 103.83 | −1.33 | −3.60 |
| biphenyl | 103.25 | 104.02 | −0.77 | −0.97 |
| diphenyl ether | 108.1 | 105.62 | 2.48 | 3.07 |
| benzophenone | 109.6 | 114.63 | −5.03 | −6.16 |
| diphenylamine | 109.7 | 113.79 | −4.09 | −4.88 |
| *n*-amylbenzene | 112.55 | 110.90 | 1.64 | 2.36 |
| diphenylmethane | 115.7 | 116.58 | −0.88 | −1.05 |
| hexamethylbenzene | 122.5 | 121.44 | 1.06 | 1.31 |
| pentabromophenol | 194 | 188.33 | 5.67 | 12.32 |

**Table 4.** Observed and Calculated Susceptibilities of Compounds in External Prediction Sets

| aliphatic compounds | $\chi_M$ ($-10^{-6}$ cgs) obsd | $\chi_M$ ($-10^{-6}$ cgs) calcd | aromatic compounds | $\chi_M$ ($-10^{-6}$ cgs) obsd | $\chi_M$ ($-10^{-6}$ cgs) calcd |
|---|---|---|---|---|---|
| α-aminobutyric acid | 62.1 | 62.27 | *p*-chloroanisole | 89.1 | 84.74 |
| isoamyl formate | 78.38 | 78.21 | *p*-chloroiodobenzene | 99.42 | 104.80 |
| sorbitol | 107.8 | 112.02 | *o*-cresol | 72.9 | 69.89 |
| 1,4-butanediol | 61.5 | 67.94 | 2,4-di-*tert*-butylphenol | 155.6 | 156.39 |
| *n*-butyraldehyde | 46.08 | 52.05 | *p*-dinitrobenzene | 68.3 | 71.23 |
| chlorodibromomethane | 75.1 | 78.17 | 2-methoxynaphthalene | 107.6 | 103.85 |
| chlorodifluoromethane | 38.6 | 48.70 | 1-naphthol | 98.2 | 96.42 |
| chlorotrifluoromethane | 45.3 | 54.99 | 1-phenyl-2-methylbutane | 113.53 | 111.65 |
| dichloroacetic acid | 58.2 | 66.99 | durene | 101.2 | 96.08 |
| dimethyl malonate | 69.69 | 63.09 | tetraphenylethylene | 217.4 | 224.20 |
| ethyl acetate | 54.1 | 51.54 | furan | 43.09 | 47.09 |
| fructose | 102.6 | 103.54 | quinoline | 86 | 87.57 |
| glucose | 102.6 | 105.27 | 4-methylpyridine | 59.8 | 65.11 |
| 2,3-hexadiene | 60.9 | 56.35 | 2,5-dimethyl-1-ethylpyrrole | 94.61 | 97.39 |
| barbituric acid | 53.8 | 43.20 | 2,5-dimethylfuran | 66.37 | 65.46 |
| cholesterol | 284.2 | 256.85 | cytosine | 55.8 | 48.74 |
| triethyl phosphate | 125.3 | 116.71 | thymidine | 57.1 | 58.22 |
| dimethyl sulfate | 62.2 | 67.54 | naphthalene | 91.9 | 91.87 |
| diethyl sulfate | 86.8 | 90.02 | phenanthrene | 127.9 | 129.52 |
| 1-heptanol | 91.7 | 94.98 | pyrene | 147.9 | 155.03 |

of the values of $\chi_M$ for haloalkanes is also observed when using other theoretical schemes.[52] For instance, the Pascal method gives errors of 7.4, 18.27, and 32 cgs for $CCl_4$, $CBr_4$, and $CI_4$, respectively. It has been recognized that, "Neither the average susceptibilities nor the principal susceptibility tensor elements of the complete halomethane series follow Pascal's additivity rules. The phenomenon is tentatively attributed to a variable paramagnetic contribution perpendicular to the C−X bond."[52b] The present scheme overestimates the values of $\chi_M$ for $CCl_4$ (18.73 cgs) and for $CBr_4$ (8.01 cgs) but produces an underestimation for $CI_4$ (−10.54 cgs). The overestimation of the diamagnetic susceptibility of haloalkanes increases dramatically in the Pascal approach when the number of halogen atoms increases in the molecule. It gives, for instance, errors of 34.37 and 34.89 cgs for ethyl and *n*-butyl perfluorobutyrates. However, the present approach gives no overestimation, with errors of −11.62 and −10.8 cgs, for these molecules, which were not included in the training series, as well as $CI_4$. These results show an important difference of the present approach compared to other (empirical) approaches to predict the diamagnetic susceptibility of organic compounds.

As we previously remarked, the present approach permits computing the contribution of any structural fragment or functional group to the diamagnetic susceptibility. The contributions of a series of structural fragments in aliphatic compounds and of a series of substituents in the phenyl ring in aromatic compounds were computed by this approach following the general scheme explained in the Appendix. They are given in Table 5 and Table 6, respectively, and allow the calculation of diamagnetic susceptibilities in an additive way.

## DIAMAGNETIC EXALTATION OF POLYCYCLIC AROMATIC COMPOUNDS

In Table 4, we can observe that the present approach permits estimation with precision of the diamagnetic susceptibilities of some polycyclic aromatic hydrocarbons (PAHs). However, in several cases these estimations show values that are not in correspondence with the experimental ones, for instance (experimental values are in parentheses): perylene, 194.46 (166.8); pyranthrene, 293.5 (266.9); dibenzocoronene, 308.66 (289.4); hexabenzocoronene 442.08 (346). These discrepancies between the calculated and experimental values are a consequence of the noninclusion of any polycyclic compound in the training series. If only PAHs are considered, the present approach shows an excellent quantitative correlation with the experimental values

**Table 5.** Diamagnetic Susceptibilities of Atomic Groups in Aliphatic Compounds

| group | $\chi_M$ ($-10^{-6}$ cgs) | group | $\chi_M$ ($-10^{-6}$ cgs) | group | $\chi_M$ ($-10^{-6}$ cgs) |
|---|---|---|---|---|---|
| −C< | 22.81 | −O−C= | -9.99 | $-CBr_3$ | 4.32 |
| −C(<)< | -9.08 | −C(=O)−O− | -10.64 | $-CI_3$ | 2.35 |
| $-C(<)_3$ | 8.46 | −C≡N | 21.43 | $-CF_2$ | -11.09 |
| *cyclo*-$C_3H_6$ | 8.46 | −C(<)−N< | -9.56 | $-CCl_2$ | -6.33 |
| −C(*cyclo*-$C_3H_5$) | -3.45 | >N−C(=O)−C< | 8.70 | $-CBr_2$ | -4.45 |
| *cyclo*-$C_4H_8$ | -3.45 | =N−C= | -9.70 | $-CI_2$ | -2.83 |
| >C=C< | 18.74 | −C(=O)−N< | -10.06 | $-CCF_2$ | 9.42 |
| =C−C= | 21.23 | −C(=O)−N(−C<)−C< | 9.18 | $-CCCl_2$ | 6.94 |
| −C(<)−C= | 22.42 | −C≡N | 14.70 | $-CCBr_2$ | 5.70 |
| −C(<)(=C<)−C< | -9.35 | −C(<)≡N | -12.54 | $-CBr_2Cl$ | 4.94 |
| −C(<)−C=C< | -10.65 | −N=O | 16.09 | $-CF_2Cl$ | 8.66 |
| −C(<)(<)−C(<)=C< | 8.53 | $-NO_2$ | -13.80 | $-CFCl$ | -8.59 |
| >C=C(<)−C< | 9.28 | $-C(=O)NO_2$ | 10.84 | $-CCBrF$ | 7.56 |
| −C≡C− | 15.63 | −C(<)−S− | 27.80 | $-CFBr$ | -7.52 |
| −C≡C−C< | -12.20 | −C(<)−C(<)−S− | -7.36 | $-CFClBr$ | 6.80 |
| ≡C−C< | 21.23 | −C(=S)−S− | -5.77 | $-CClBr$ | -5.36 |
| ≡C−C≡ | 19.59 | $-CF$ | 20.00 | $-CCl_2Br$ | 5.56 |
| >C=O | 16.09 | $-CCl$ | 26.91 | −C(Cl)−C= | -7.79 |
| −C(<)−C=O | -11.58 | $-CBr$ | 30.06 | $>C=CF_2$ | 7.84 |
| −O−C=O | -12.82 | $-CI$ | 33.26 | >C(Br)−C= | -6.75 |
| >N−C=O | -13.14 | $-CCF$ | -10.06 | >C(Cl)−C= | -5.77 |
| $-CO_2^-$ | 10.25 | $-CCCl$ | -7.66 | $-OCCl_2$ | 7.32 |
| −C(<)(=O)−N< | 10.39 | $-CCBr$ | -6.63 | −O−C(Cl)(<)−C< | 8.08 |
| =C=O | 19.09 | $-CCI$ | -5.66 | −O−C(=O)−Cl | -8.39 |
| =C−N< | 20.00 | $-CCFC-$ | 8.94 | $-CCl_2N<$ | 7.42 |
| −C(<)(=C<)−O | -10.50 | $-CCCl(<)-$ | 7.70 | −C(Cl)=N< | -8.59 |
| −C(<)(=O)−C(<)−C< | 9.70 | $-CCBr(<)-$ | 7.08 | ABCD | -1.724 |
| −C(<)=O | 20.62 | $-C(Cl)(<)-$ | 6.42 | A(BCD) | -10.35 |
| −C(<)(<)=O | -9.85 | $-CF_3$ | 9.91 | intercept | 1.27 |
| −O−C(<)(<)−C< | 8.84 | $-CCl_3$ | 6.18 | | |

of $-\chi_M$, which is given by

$$-\chi_M \times 10^{-6}\,(\text{cgs}) = 37.284 + 54.533\mu_0 - 44.262\mu_1 + 0.264\mu_5 - 0.052\mu_6 \quad (10)$$

with a correlation coefficient of 0.9948 and a standard deviation of only 8.13 cgs for the 20 PAHs included in the model. The experimental and calculated values of $-\chi_M$ for these 20 compounds as well as for other nine PAHs used as an external prediction set are given in Table 7.

While the standard deviation of the regression model found represents only 4.4% of the mean susceptibility for the 20 PAHs in the training set, this error is equal to 22.28 cgs for the external prediction set of PAHs (see Table 7). This is produced by the great discrepancy in the prediction of the susceptibility of ovalene, for which an error of 54.98 cgs is obtained. When this compound is excluded from the analysis, the root of the mean square error obtained is only 8.69 cgs. It is known that other methods also underestimate the diamagnetic susceptibility of ovalene. For instance, Pascal's approach gives an error of 52.62 cgs,[17] which is very similar to that obtained with the present theoretical approach. Dorfman[17] has explained this "anomaly" by assuming that the $\pi$-electrons are concentrated on the periphery of the molecule. Pascal's approach[17,23] also produces large errors in the estimation of the susceptibility for other PAHs, for instance violanthrene and hexabenzocoronene, for which errors of 46.62 and −48.26 cgs are obtained, respectively, while the present approach gives errors of only −3.62 and −3.82 cgs for these compounds.

The diamagnetic susceptibility exaltation is defined as the difference between the experimental diamagnetic susceptibility of an organic compound and a hypothetical value of it defined by considering bond localization in the molecule.[33−39] Consequently, we propose the use of models 8 and 10 to compute the diamagnetic susceptibility exaltation $\Lambda$ of organic compounds. The values of the exaltation are calculated as the difference between diamagnetic susceptibility calculated by model (10) and the corresponding one obtained from model 8, representing the susceptibility for a hypothetical bond-localized structure. The values of the susceptibility exaltations so calculated for the 29 PAHs studied here are given in Table 7. In this table we also show the values of $-\Lambda$ reported recently by Bird[53] for these compounds. Both measurements of diamagnetic susceptibility exaltations are linearly interrelated, showing a correlation coefficient of 0.8970.

## MAGNETOOPTIC ROTATION (FARADAY EFFECT)

The quantitative model expressing the values of the molar magnetic rotation [MMR] in terms of the spectral moments of the bond matrix is given by eq 11 for aliphatic compounds:

$$[\text{MMR}] = -13.611 + 9.113\mu_1 - 1.352\mu_0\mu_2 + 0.844\mu_1\mu_2 + 10.077(\mu_0)^2 - 8.321\mu_0\mu_1 + 1.267(\mu_1)^2 + 2.899 \quad (11)$$

This model explains 90% ($R = 0.950$) of the variance in the magnetooptical effect for 61 studied compounds. The standard deviation of the regression is 0.73 and the root-mean-square error is equal to 0.81. In developing this model four compounds were detected as statistical outliers. They were cyclopentadiene, 2-methyl-1,3-butadiene, 1,3-butadiene, and 1,3-pentadiene. In all these cases the values calculated by model 11 are significantly lower than the experimental magnetooptic rotation. As can be seen, these four compounds have conjugated double bonds in their structures. Consequently, the greater than expected experimental values of the Faraday effect in these compounds is related to the exaltation of this effect due to the delocalization of $\pi$-elec-

**Table 6.** Diamagnetic Susceptibilities of Functional Groups in Benzene Derivatives

| group | $\chi_M$ ($-10^{-6}$ cgs) | group | $\chi_M$ ($-10^{-6}$ cgs) | group | $\chi_M$ ($-10^{-6}$ cgs) |
|---|---|---|---|---|---|
| −F | 1.50 | −COOH | 10.95 | −I | 32.22 |
| −OH | 3.01 | −SH | 20.53 | $-n-C_4H_9$ | 43.92 |
| −CHO | 7.79 | $-CH_2OH$ | 17.66 | $-i-C_4H_9$ | 41.02 |
| $-NO_2$ | 7.59 | $-COCH_3$ | 17.03 | −Ph | 48.01 |
| $-NH_2$ | 7.58 | $-CONH_2$ | 12.82 | −OPh | 49.61 |
| −CN | 0.22 | $-CH_2NH_2$ | 19.22 | −COPh | 58.63 |
| −NO | 3.46 | −COCl | 27.59 | −NHPh | 57.78 |
| $-CH_3$ | 9.12 | $-C_2H_5$ | 21.96 | $-n-C_5H_{11}$ | 54.90 |
| $-NHNH_2$ | 11.36 | $-OCH_3$ | 12.18 | $-CH_2Ph$ | 60.58 |
| −NHOH | 14.07 | −Br | 23.73 | ortho | 1.78 |
| −Cl | 16.56 | −SCN | 33.36 | | |

**Table 7.** Observed and Calculated Diamagnetic Susceptibilities, Diamagnetic Susceptibility Exaltations Calculated in the Present Work and that Reported by Bird, and Resonance Energies of Polycyclic Aromatic Compounds (PAHs)

| compound | $\chi_M$ (expt)[b,c] ($-10^{-6}$ cgs) | $\chi_M$ (calcd)[d] ($-10^{-6}$ cgs) | $\Lambda$[e] ($-10^{-6}$ cgs) | $\Lambda$[f,g] ($-10^{-6}$ cgs) |
|---|---|---|---|---|
| benzene | 54.84 | 55.53 | 11.11 | 14.5 |
| naphthalene | 91.9 | 94.93 | 40.06 | 27.54 |
| anthracene | 130 | 133.71 | 68.40 | 42.4 |
| tetracene | 168 | 172.49 | 96.73 | 56.7 |
| pentacene | 205.4 | 211.27 | 125.07 | 70.7 |
| pyrene | 147.9 | 151.59 | 93.67 | 57.4 |
| coronene | 243.3 | 225.52 | 171.93 | 102.9 |
| ovalene[a] | 353.8 | 298.82 | 249.57 | 170.6 |
| chrysene | 166.67 | 158.50 | 86.19 | 55.7 |
| phenanthrene[a] | 127.9 | 126.72 | 63.13 | 40 |
| hexabenzocoronene | 346 | 349.82 | 297.41 | 106.3 |
| dibenzopyrene[a] | 213.6 | 214.54 | 139.18 | 69.2 |
| pyranthrene | 266.9 | 270.59 | 192.17 | 85.4 |
| perylene | 166.8 | 175.76 | 110.84 | 45.8 |
| biphenyl[a] | 103.25 | 101.22 | 31.97 | 25.1 |
| dibenzocoronene | 289.4 | 280.94 | 224.30 | 115.9 |
| *p*-terphenyl | 152 | 146.91 | 52.82 | 36.7 |
| triphenylene | 156.6 | 150.89 | 80.30 | 45.3 |
| benzo[*a*]pyrene | 194 | 183.07 | 116.42 | 73 |
| dibenz[*a*,*h*]anthracene | *c* | 197.28 | 146.66 | 58.3 |
| dibenz[*c*,*g*]phenanthrene | 203 | 182.36 | 103.06 | 81 |
| violanthrene | 273.5 | 277.12 | 173.18 | 118 |
| acenaphthylene | 111.6 | 117.19 | 67.99 | 37.4 |
| fluoranthrene | 138.0 | 140.12 | 83.92 | 40.4 |
| acenaphthanthracene[a] | 184 | 159.73 | 77.26 | 63 |
| anthanthrene | 204.2 | 207.64 | 114.53 | 73.5 |
| acenaphthene[a] | 109.3 | 103.38 | 40.09 | *g* |
| 1,2,5,6-dibenzofluorene | 184 | 173.44 | 90.34 | *g* |
| fluorene[a] | 110.5 | 110.44 | 44.78 | *g* |

[a] Compound used in an external prediction set. [b] Taken from ref 51. [c] Value not reported in ref 22. [d] Calculated from eq 19. [e] Value calculated in the present work. [f] Value taken from Bird, ref 18. [g] Value not reported in ref 18.

trons in their structures. It is well-known that the exaltation of magnetic properties in conjugated $\pi$-electrons systems produces an increment in the values of the corresponding properties compared to those expected if the electrons were "frozen" in the double bonds. The values of the experimental and calculated values of [MMR] are given in Table 8.

The predictive capacity of model 11 is shown by calculating the molar magnetic rotation [MMR] for a series of 20 aliphatic compounds not included in the training set used to develop the corresponding model. The calculated and experimental values of the molar magnetic rotation for the compounds in the prediction set are given in Table 9. It can be seen that the root-mean-square error for the prediction of this property for compounds in the prediction set is 0.83, which is similar to that obtained by the leave-one-out cross-validation of model 11.

The quantitative model obtained for the aromatic compounds is given by

$$[\mathrm{MMR}] = 6.784 - 15.828\mu_0 + 24.506\mu_2 - 16.424\mu_3 + 4.173\mu_4 - 0.361\mu_5 \quad (12)$$

This model explains more than 95% ($R = 0.976$) of the variance in the Faraday effect of the aromatic compounds studied. The apparently higher standard deviation (1.89) as well as root-mean-square error (2.07) compared to those of model 11 is only due to the higher value of the mean molar magnetic rotation for aromatic compounds compared to that of the aliphatic ones. For instance, the mean molar magnetic rotation for aromatic compounds is 15.61 compared to the value of 5.61 for the aliphatic ones. The experimental and calculated values of [MMR] are given in Table 10.

**Table 8.** Calculated and Experimental Values of the Magnetooptic Rotation (Faraday effect) of Aliphatic Compounds in the Training Set

| compound | expt[a] | calcd[b] | res[c] | compound | expt[a] | calcd[b] | res[c] |
|---|---|---|---|---|---|---|---|
| 1-nitropropane | 3.82 | 4.49 | −0.67 | nonane | 9.7 | 9.68 | 0.02 |
| 1-butene | 5.53 | 3.97 | 1.56 | decane | 10.7 | 10.88 | −0.18 |
| butane | 4.59 | 4.84 | −0.25 | nitromethane | 1.86 | 1.96 | −0.10 |
| isobutane | 4.87 | 4.53 | 0.34 | urea | 2.38 | 1.96 | 0.42 |
| maleic anhydride | 4.5 | 4.50 | 0.00 | vinyl bromide | 6.22 | 5.12 | 1.10 |
| acetic anhydride | 4.28 | 4.43 | −0.15 | ethylene oxide | 1.935 | 3.29 | −1.36 |
| *n*-butyric acid | 4.47 | 4.54 | −0.07 | acetaldehyde | 2.38 | 2.60 | −0.22 |
| ethyl acetate | 4.47 | 4.49 | −0.02 | acetic acid | 2.525 | 2.14 | 0.38 |
| methyl propanoate | 4.37 | 4.49 | −0.12 | 1,2-dichloroethane | 5.49 | 5.82 | −0.33 |
| methyl 2-hydroxypropanoate | 4.66 | 4.18 | 0.48 | ethylidene dichloride | 5.33 | 5.81 | −0.48 |
| ethoxyethane | 4.78 | 4.98 | −0.20 | ethylidene dibromide | 9.7 | 8.45 | 1.25 |
| cyclopentadiene[d] | 7.03 | 4.57 | 2.46 | bromoethane | 5.85 | 7.03 | −1.18 |
| *sec*-butyl alcohol | 4.91 | 4.66 | 0.25 | iodoethane | 10.07 | 8.93 | 1.14 |
| cyclopentene | 5.69 | 5.10 | 0.59 | ethanol | 2.78 | 3.54 | −0.76 |
| cyclopentane | 4.89 | 6.01 | −1.12 | ethylenemercaptan | 5.52 | 5.93 | −0.41 |
| pentane | 5.6 | 5.65 | −0.05 | ethyleneamine | 3.61 | 3.74 | −0.13 |
| nitroethane | 2.84 | 3.19 | −0.35 | dichloroacetic acid | 5.3 | 4.93 | 0.37 |
| 1,5-pentanediamine | 7.49 | 7.28 | 0.21 | acrolein | 4.74 | 3.28 | 1.46 |
| propyl acetate | 5.45 | 5.91 | −0.46 | 1-octanol | 8.88 | 9.68 | −0.80 |
| hexane | 6.22 | 6.54 | −0.32 | allyl alcohol | 4.68 | 3.67 | 1.01 |
| 2-methyl-1,3-butadiene[d] | 8.8 | 3.35 | 5.45 | propyl alcohol | 3.33 | 4.36 | −1.03 |
| chlorocyclohexane | 7.5 | 8.27 | −0.77 | acetone | 3.472 | 2.66 | 0.81 |
| 2-hexanol | 6.89 | 6.50 | 0.39 | ethyl formate | 3.56 | 4.62 | −1.06 |
| 2-methyl-3-pentanol | 6.9 | 5.69 | 1.21 | methyl acetate | 3.42 | 3.49 | −0.07 |
| 1-heptene | 8.48 | 7.21 | 1.27 | propyl bromide | 6.88 | 7.23 | −0.35 |
| heptane | 7.61 | 7.50 | 0.11 | isopropyl bromide | 7 | 7.56 | −0.56 |
| 1-heptanol | 7.85 | 8.46 | −0.61 | 1-propanol | 3.77 | 4.29 | −0.52 |
| 2-heptanol | 7.94 | 7.54 | 0.40 | 2-propanol | 3.9 | 3.75 | 0.15 |
| 1-octene | 9 | 8.45 | 0.55 | 1,2,3-propanetriol | 4.11 | 4.88 | −0.77 |
| 2-octene | 9.33 | 8.46 | 0.87 | 1,3-butadiene[d] | 7.94 | 3.40 | 4.54 |
| octane | 8.65 | 8.55 | 0.10 | 1-butanol | 4.6 | 5.27 | −0.67 |
| 3-octanol | 8.9 | 8.66 | 0.24 | 1,3-pentadiene[d] | 8.8 | 4.63 | 4.17 |
| ethyl propanoate | 5.46 | 5.91 | −0.45 | | | | |

[a] Taken from ref 51. [b] Calculated from eq 11. [c] Experimental minus calculated. [d] Statistical outlier.

**Table 9.** Calculated and Experimental Values of the Magnetooptic Rotation (Faraday Effect) of Aliphatic Compounds in the External Prediction Set

| compound | expt[a] | calcd[b] | res[c] | compound | expt[a] | calcd[b] | res[c] |
|---|---|---|---|---|---|---|---|
| chloroacetic acid | 3.89 | 3.83 | 0.06 | 1-decene | 11.65 | 11.17 | 0.48 |
| isopropyl chloride | 5.16 | 5.97 | −0.81 | acetonitrile | 2.32 | 2.26 | 0.06 |
| 1-chloropropane | 5.04 | 5.95 | −0.91 | methyl formate | 2.49 | 3.28 | −0.79 |
| 2-methyl-1-propanol | 4.94 | 4.66 | 0.28 | chloroethane | 4.04 | 5.55 | −1.51 |
| 1-pentene | 6.45 | 5.29 | 1.16 | glycol | 2.94 | 3.97 | −1.03 |
| 2-oxopropanoic acid | 3.56 | 2.67 | 0.89 | isopentane | 5.75 | 5.23 | 0.52 |
| 3-hexanol | 6.85 | 6.50 | 0.35 | propanoic acid | 3.462 | 3.30 | 0.16 |
| heptanal | 7.42 | 8.52 | −1.10 | isopropyl bromide | 11.18 | 9.57 | 1.61 |
| 3-heptanol | 7.86 | 7.54 | 0.32 | *n*-propylamine | 4.56 | 4.53 | 0.03 |
| 2-octanol | 9 | 8.66 | 0.34 | cyclohexane | 5.66 | 6.88 | −1.22 |

[a] Taken from ref 51. [b] Calculated from eq 12. [c] Experimental minus calculated.

The good predictive capacity of this model is reaffirmed by using a prediction set of 10 compounds for which the magnetooptic rotation was calculated and whose values (experimental and calculated) are given in Table 11. The value of the root-mean-square error for this prediction set (2.02) is very close to that obtained by the leave-one-out cross-validation of the training set (2.07).

## CONCLUSIONS

In most of our previous reports we have stated the necessity of crossing the previously established frontiers for chemical graph theory. This necessity has been clearly remarked by Milne's statement that,[2] "Continued manipulation of alkanes, with the generation of more matrices and topological indices, is doubtless attractive (and safe), but if such work addresses any real problems, they are for the most part problems in mathematics, not chemistry. The chemistry community has many real problems in the interpretation of chemical structure−property relationships and will support, even collaborate, with serious attempts from graph theory school to resolve such problems."

The current work is an attempt in the direction of deriving structure−property relationships with structural interpretability for chemists. The possibility of finding quantitative contributions of different fragments to the studied properties that the TOSS-MODE approach offers is a step forward in the search of QSPR models. However, the main advantage of this approach, as manifested in the current work, is not based on the fact that fragment and group contributions to the diamagnetic susceptibility and optical power rotation can be straightforwardly derived. The great advantage is that these contributions can be found for groups and fragments present in molecules for which experimental values of the

**Table 10.** Calculated and Experimental Values of the Magnetooptic Rotation (Faraday Effect) of Aromatic Compounds in the Training Set

| compound | expt | calcd | res | compound | expt | calcd | res |
|---|---|---|---|---|---|---|---|
| thiophene | 9.4 | 8.31 | 1.09 | *m*-xylene | 12.82 | 13.53 | −0.71 |
| furan | 5.48 | 5.86 | −0.38 | *p*-xylene | 12.8 | 13.53 | −0.73 |
| furfural | 7.01 | 9.35 | −2.34 | *o*-ethyltoluene | 14.56 | 15.89 | −1.33 |
| benzene | 11.27 | 9.90 | 1.37 | 1,3,5-trimethylbenzene | 13.36 | 15.35 | −1.99 |
| *p*-dichlorobenzene | 13.55 | 17.63 | −4.08 | naphthalene | 24.98 | 24.26 | 0.72 |
| fluorobenzene | 9.96 | 10.00 | −0.04 | 1-bromonaphthalene | 31.05 | 28.58 | 2.47 |
| bromobenzene | 14.51 | 15.73 | −1.22 | 2-naphthol | 27.1 | 24.70 | 2.40 |
| iodobenzene | 19.11 | 18.08 | 1.03 | ethyl phenylacetate | 14.99 | 15.70 | −0.71 |
| phenol | 12.07 | 10.34 | 1.73 | ethyl methylsalicylate | 17.14 | 18.88 | −1.74 |
| 1,3-dinitrobenzene | 9.65 | 8.23 | 1.42 | 1,2-diphenylbenzene | 40.2 | 40.07 | 0.13 |
| nitrobenzene | 9.36 | 9.07 | 0.29 | 1,3-diphenylbenzene | 41 | 40.69 | 0.31 |
| toluene | 12.16 | 11.72 | 0.44 | *o*-methylphenol | 13.38 | 11.40 | 1.98 |
| *o*-chlorotoluene | 13.72 | 14.20 | −0.48 | *p*-methylphenol | 12.86 | 12.16 | 0.70 |
| *p*-chlorotoluene | 13.25 | 15.58 | −2.33 | *p*-toluidine | 15.92 | 12.51 | 3.41 |
| *o*-bromotoluene | 15.67 | 15.84 | −0.17 | *m*-toluidine | 16.91 | 12.51 | 4.40 |
| *o*-nitrotoluene | 10.8 | 9.92 | 0.88 | ethyl *o*-toluate | 15.06 | 15.41 | −0.35 |
| *p*-nitrotoluene | 10.2 | 10.88 | −0.68 | ethyl *p*-toluate | 14.74 | 16.36 | −1.62 |
| ethylbenzene | 13.41 | 15.09 | −1.68 | | | | |

**Table 11.** Calculated and Experimental Values of the Magnetooptic Rotation (Faraday Effect) of Aromatic Compounds in the External Prediction Set

| compound | expt | calcd | res |
|---|---|---|---|
| *o*-xylene | 13.36 | 12.51 | 0.85 |
| chlorobenzene | 12.51 | 13.77 | −1.26 |
| *m*-bromotoluene | 15.09 | 17.55 | −2.46 |
| benzonitrile | 11.85 | 12.98 | −1.13 |
| 1-chloronaphthalene | 28.15 | 26.94 | 1.21 |
| *m*-ethyltoluene | 14.18 | 16.91 | −2.73 |
| propyl benzoate | 14.87 | 15.96 | −1.09 |
| *m*-methylphenol | 12.77 | 12.16 | 0.61 |
| aniline | 16.08 | 11.43 | 4.65 |
| phenanthrene | 39.7 | 37.99 | 1.71 |

corresponding properties are not available. This is unimaginable with experimentally based approaches such as Pascal's or related ones. Hence, the current graph theoretical approach opens novel possibilities for chemists interested in the interpretation of real chemical problems by structure−property relationships.

Finally, we remark that the TOSS-MODE approach has been derived from mathematical (algebraic) manipulation of chemical graphs and it has been evolving to be adapted to chemical reality. By this means, Milne[2] was right in pointing that the work together of mathematics and chemistry "is an opportunity for significant progress in this lively area of theoretical chemistry" and is exemplified with this graph theoretical approach.

## APPENDIX

To find the contribution of the different fragments to any of the properties studied here, now designed simply by *P*, we use the following approach. According to the maximal order of the spectral moments included in the QSPR model, we identify the "size" of the fragments contributing to the studied property. For instance, the maximal order of the spectral moments included in models 8 and 9 is 4, i.e., $\mu_4$. This means that the fragments contributing to $-\chi_M$ in aliphatic and aromatic compounds have not more than three bonds. After this, we build all the fragments containing three bonds and any kind of heteroatom. For instance, A−B represents a two-atom fragment in which A and B are any atom, such as C−C, C═C, C−O, C−N, and C═O. Other fragments are A(BC), such as C−C−C, O−N−O, and O═C−O; A(BCD) such as $C(Cl)_3$ and $C(Br_2Cl)$; A(BCDE) as the *tert*-butyl group; linear fragments A−B−C−D such as C−C−C−C and C−O−C−C; and fragments A(BCD−E) such as C−C(Cl)−C−C and C−C(═O)−C−C.

The contribution of any of these fragments to the property *P* is given by the following coefficients: $b_{AB}$, $b_{A(BC)}$, $b_{A(BCD)}$, $b_{A(BCDE)}$, $b_{A-B-C-D}$, $b_{A(BCD-E)}$. These coefficients are computed by using the following mathematical expressions:

$$b_{AB} = a_0 + a_1 d_{AB} + a_2 (d_{AB})^2 + a_3 (d_{AB})^3 + a_4 (d_{AB})^4 + a_5 (d_{AB})^5 + a_6 (d_{AB})^6 \quad (13)$$

$$b_{A(BC)} = 2a_2 + 3a_3 (d_{AB} + d_{AC}) + a_4 \{2 + 4[(d_{AB})^2 + (d_{AC})^2] + 4(d_{AB} d_{AC})\} + a_5 [5({d_{AB}}^3 {d_{AC}}^3) + 5({d_{AB}}^2 d_{AC} + d_{AB} {d_{AC}}^2) + 5(d_{AB} d_{AC})] + a_6 [6({d_{AB}}^2 {d_{AC}}^2) + 6(d_{AB} {d_{AC}}^3) + 5({d_{AB}}^3 d_{AC}) + 6({d_{AB}}^4 {d_{AC}}^4)] + 9({d_{AB}}^2 {d_{AC}}^2) + 12(d_{AB} d_{AC}) + 2] \quad (14)$$

$$b_{A(BDC)} = 6a_3 + a_4 [12 + 8(d_{AB} + d_{AC} + d_{AD}) + a_5 [(30 + 10[({d_{AB}}^2 + {d_{AC}}^2 + {d_{AD}}^2)] + 20[(d_{AB} + d_{AC} + d_{AD})] + 10[(d_{AB} d_{AC} + d_{AB} d_{AD} + d_{AC} d_{AD})] + a_6 [12({d_{AB}}^3 + {d_{AC}}^3 + {d_{AD}}^3) + 12({d_{AB}}^2 d_{AC} + d_{AB} {d_{AC}}^2 + d_{AB} {d_{AC}}^2 + {d_{AB}}^2 d_{AD} + d_{AC} {d_{AD}}^2 + {d_{AC}}^2 d_{AD}) + 30({d_{AB}}^2 + {d_{AC}}^2 + {d_{AD}}^2) + 36(d_{AB} d_{AC} + d_{AB} d_{AD} + d_{AC} d_{AD}) + 60(d_{AB} + d_{AC} + d_{AD}) + 12(d_{AB} d_{AC} d_{AD}) + 60] \quad (15)$$

$$b_{A(BCDE)} = a_5 [(120 + 30(d_{AB} + d_{AC} + d_{AD} + d_{AE}) + a_6 [36[({d_{AB}}^2 + {d_{AC}}^2 + {d_{AD}}^2 + {d_{AE}}^2)] + 24(d_{AB} d_{AC} + d_{AB} d_{AD} + d_{AB} d_{AE} + d_{AC} d_{AD} + d_{AC} d_{AE} + d_{AD} d_{AE}) + 180(d_{AB} + d_{AC} + d_{AD} + d_{AE}) + 480] \quad (16)$$

$$b_{A-B-C-D} = a_5[5(d_{AB} + d_{CD}) + 10d_{BC}] + a_6[6[(d_{AB}^2 + d_{CD}^2) + 18d_{BC}^2 + 12(d_{AB}d_{BC} + d_{BC}d_{CD}) + 6(d_{AB}d_{CD}) + 12] \quad (17)$$

$$b_{A(BCD-E)} = 10a_5 + a_6[12(d_{AB} + d_{AC} + d_{DE}) + 24(d_{AD})] + 24 \quad (18)$$

In these expressions $d_{AB}$ is the weight used for the bond A−B and the $a_i$'s are the coefficients in models 4 and 5.

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