

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/233409142>

# Substituent effects on O–H and S–H bond dissociation enthalpies of disubstituted phenols and thiophenols

ARTICLE in INTERNATIONAL JOURNAL OF QUANTUM CHEMISTRY · MARCH 2008

Impact Factor: 1.43 · DOI: 10.1002/qua.21522

CITATIONS

7

READS

123

## 4 AUTHORS, INCLUDING:



**Daniel J. V. A. dos Santos**

University of Lisbon

52 PUBLICATIONS 354 CITATIONS

SEE PROFILE



**Raul J. Bernardino**

Instituto Politécnico de Leiria

19 PUBLICATIONS 250 CITATIONS

SEE PROFILE



**Rita C Guedes**

University of Lisbon

69 PUBLICATIONS 935 CITATIONS

SEE PROFILE

# Substituent Effects on O–H and S–H Bond Dissociation Enthalpies of Disubstituted Phenols and Thiophenols

DANIEL J. V. A. dos SANTOS,<sup>1</sup> ANA S. NEWTON,<sup>1</sup>  
RAUL BERNARDINO,<sup>2</sup> RITA C. GUEDES<sup>1</sup>

<sup>1</sup>iMed.Ul/CECF, Faculty of Pharmacy, University of Lisbon, Av. Prof. Gama Pinto,  
1649-003 Lisbon, Portugal

<sup>2</sup>Instituto Politécnico de Leiria, Escola Superior Tecnologia do Mar, Santuário N.ª Sra. dos Remédios,  
Apartado 126, 2524-909 Peniche, Portugal

Received 25 June 2007; accepted 16 July 2007

Published online 10 October 2007 in Wiley InterScience (www.interscience.wiley.com).

DOI 10.1002/qua.21522

**ABSTRACT:** The O–H and S–H homolytic bond dissociation enthalpies of a set of disubstituted phenols and thiophenols (NH<sub>2</sub>, OH, CH<sub>3</sub>, Cl, CF<sub>3</sub>, and NO<sub>2</sub>) have been computed by a density functional theory procedure with the 6-311++G(d,p) basis set. A very good agreement between our results and available experimental ones is observed. The effect of substituents on structure, charges and BDEs are investigated and their correlation with Hammett parameters is studied. © 2007 Wiley Periodicals, Inc. *Int J Quantum Chem* 108: 754–761, 2008

**Key words:** phenol; thiophenol; antioxidant; bond dissociation enthalpies; DFT; disubstituted

## 1. Introduction

Although the number of accurate experimental bond dissociation energies (BDEs) is still very small, it is a very important property to understand chemical reactivity and also to design new molecules with specific chemical purposes. For instance, this property is crucial to find the antioxidant power of a

compound [1]. Antioxidants are known to inhibit the chain reaction of peroxy radicals (ROO•) through a mechanism of hydrogen atom transfer to the radical, in the following way:



Although other properties should also be taken into account when designing a new safe and effective antioxidant molecule like no direct reaction with molecular oxygen, higher ionization energy or radical stability against oxygen [2], the antioxidant power will depend on the stability of the ArO• radical.

Correspondence to: R. C. Guedes; e-mail: rguedes@ff.ul.pt  
Contract grant sponsor: sfRH/BPD.  
Contract grant number: 1815/2004.

Phenolic compounds are in the center of a class with great biological and commercial importance, namely by their antioxidation power. They are widely distributed in plants and constitute phytochemical materials belonging to three important groups: flavonoids, phenolic acids, and polyphenols (tannins). Phenolic compounds possess disease-preventive properties towards heart diseases, cancer, or diabetes [3, 4]. Because of their very effective antioxidant power, they also have antiaging properties [5, 6]. Therefore, a study of the effect of substitution on the BDEs of  $\text{PhO-H}$ , assumes a central role to understand and predict the antioxidant power of these compounds.

Sulphur-centered radicals are also very important in chemistry since they are an important class of intermediates for specialized organic synthesis [7, 8]. In oxidative stress, they are involved in the early stages of oxidative attack associated with aging and age-related pathologies such as Alzheimer [5, 6]. They are also involved in important environmental issues, like wastewater treatment and biosolid removal of odors [9].

The antioxidant power of thiol compounds is due to the weaker  $\text{S-H}$  bond. The sulphur atom can easily accommodate the loss of a single electron resulting from the homolytic cleavage of the  $\text{S-H}$  bond, providing extra stability to the generated radical species. However, the direct gas phase BDEs measurement for compounds containing  $\text{S-H}$  bonds through experimental methods is difficult, specially for those that are difficult to vaporize [10]. Therefore, the experimental gas-phase  $\text{S-H}$  BDEs are only known for a limited number of small thiols such as  $\text{H}_2\text{S}$ ,  $\text{CH}_3\text{SH}$ , and  $\text{CH}_3\text{CH}_2\text{SH}$ , making theoretical methods important to predict the properties of this type of molecules.

It is possible to calculate the BDEs of  $\text{ArO-H}$  or  $\text{ArS-H}$  using, as a reference, the BDE of phenol ( $\text{PhO-H}$ ) or thiophenol ( $\text{PhS-H}$ ) and then adding a contribution (positive or negative) from each one of the ring substituents [11]. There are several studies on the determination of bond dissociation enthalpies of phenolic derivatives, relating the strength of the phenolic bond with the nature, position, and number of substituents [12]. It is worth mentioning that the idea of the addition of electron-withdrawing substituents has been investigated [11, 13, 14] because it is believed to be associated with an enhancement of the  $\text{X-H}$  ( $\text{X=O}$ ,  $\text{S}$ ) BDE values and therefore with both a decrease of the antioxidant activity and a reduction of the persistence due to an increased reactivity of the related phenoxyl radicals.

Although it is difficult to anticipate if a specific substituent effect will be more important to the thermodynamic stability of the phenoxyl radical or to the precursor phenolic compound, it is believed that, for instance, electron-donor groups in the *para* position will decrease the  $\text{ArO-H}$  bond dissociation enthalpy,  $\Delta H^0$ , mainly because of a stabilization of the phenoxyl radical. On the other hand, the increase in  $\text{ArO-H}$   $\Delta H^0$ , caused by electron-withdrawing groups in the same position, is mainly attributed to a stabilization of the parent phenol [11].

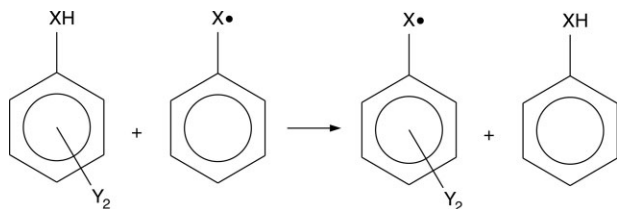
The rationalization of the effect on the BDEs by added substituents can be difficult. This task is even more difficult when more than one substituent group is added to a molecule in different positions. Nevertheless, state of the art quantum calculations can provide insight into how the BDEs are affected by the substituents. In the present work we present a quantum mechanics study of the di-substitution effect in phenols and thiophenols on the  $\text{X-H}$  ( $\text{X=O}$ ,  $\text{S}$ ) BDEs.

## 2. Theoretical and Methodological Approach

All structures (molecules and respective radicals) have been fully optimized without symmetry constraints using the Becke three-parameter hybrid functional (B3LYP [15]) method, which is well known to produce accurate geometries. A recent study proved that this functional provided more accurate energies than other computationally more demanding methods (like Møller-Plesset and coupled cluster methods) [16]. The 6-311++G(d,p) [17] relatively large basis set has been used to reduce basis set truncation and basis set superposition errors. The vibrational frequency calculations were performed at the same level of theory to check that all structures were global minima of the potential energy surface (absence of negative vibrational frequencies) and to correct the computed energies for zero-point energies as well as translational, rotational, and vibrational contributions to the enthalpy. All calculations have been performed with the Gaussian03 software package [18].

While searching for minimum energy conformations several initial geometries were used, specially in those cases were intramolecular hydrogen bonds are possible. In those cases, the number and type of hydrogen bonds ( $\text{O}\cdots\text{H}$  or  $\text{H}\cdots\text{S}$ ) were also tested.

The relative BDEs ( $\Delta D$ ) to phenol or thiophenol are calculated as the enthalpy difference at 298 K for the reaction ( $X=O, S$ ;  $Y$  is the substituent) (Scheme 1):



and the absolute BDE values are obtained by adding the  $\Delta D$  of a di-substituted compound to the selected  $\text{PhO-H}$  ( $371.3 \text{ kJ mol}^{-1}$ ) or  $\text{PhS-H}$  ( $349.4 \text{ kJ mol}^{-1}$ ) BDEs, respectively.

The studied substituents were chosen based on their ability to donate or accept electrons since it is expected that this property can influence the bond dissociation enthalpies. For the series studied, the electron donor character decreases in the following order:  $\text{NH}_2 > \text{OH} > \text{CH}_3 > \text{Cl} > \text{CF}_3 > \text{NO}_2$ .

### 3. Results and Discussion

We have tested the di-substitution effect of six different chemical substituents ( $\text{NH}_2$ ,  $\text{OH}$ ,  $\text{CH}_3$ ,  $\text{Cl}$ ,  $\text{CF}_3$ , and  $\text{NO}_2$ ) on phenols and thiophenols, upon the dissociation energy of  $\text{O-H}$  and  $\text{S-H}$  bonds. The effects of these substituents on the geometries, natural bond orbital (NBO) charges and BDEs were calculated and are shown in Tables I and II alongside with other theoretical or experimental values already published, when available.

On Table I it is observed that the addition of a  $\text{NH}_2$ ,  $\text{OH}$ ,  $\text{Cl}$ , and  $\text{NO}_2$  group in the *ortho* position increases the  $\text{O-H}$  bond length independently of the second substituent position. This effect is specially noticeable for  $\text{NO}_2$  and  $\text{NH}_2$ . The addition of these substituents in the *meta* and/or *para* positions and the addition of  $\text{CH}_3$  or  $\text{CF}_3$  has no influence in the  $\text{O-H}$  bond length.

Except for  $\text{CH}_3$ , the substitution generally reduces the  $\text{C-O}$  bond length. With this substituent, the  $\text{C-O}$  bond length increases. A different behavior is also found for the *meta* and/or *para* substitutions which have a less pronounced effect than the *ortho* substitutions (the bond lengths are closer to the bond length of phenol).

Although there is no clear trend for the  $\text{C-O}^\bullet$  bond length changes, except in two cases, this length

is always less than the  $\text{C-O}$  bond for the same substitution.

The substituents have an impact upon the phenolic oxygen charges. A dependency between the phenolic oxygen charges and the electron acceptor or donator character of the substituent is found. Although  $\text{OH}$  and  $\text{CH}_3$  substitutions showed almost no impact on the phenolic oxygen charge, groups like  $\text{NO}_2$ ,  $\text{CF}_3$ , or  $\text{Cl}$  decrease, while  $\text{NH}_2$  increases the charge. This change has also a big impact in the BDEs where a clear correlation between the increasing in the phenolic oxygen charge and the increasing of the BDEs exists (cf. Fig. 1). This observation implies that an electron donor/acceptor substituent will, in general, decrease/increase the BDE.

The 2,3  $\text{CH}_3$  substitution was not included in Figure 1, since the oxygen charge is too low ( $-0.884$ ) when compared with all other values. We have also calculated ChelpG, Merz-Kollman-Singh and Mulliken charges (not included) and found that in these schemes this partial charge is close to the other values for the same substituent.

For thiophenols, the changes on the  $\text{S-H}$  bond lengths was less noticeable and there is no clear correlation neither with the substituent or position. The addition of  $\text{NH}_2$  and  $\text{CH}_3$  increases the  $\text{C-S}$  bond lengths while, in general, the addition of all other groups decreases this bond length.

As can be seen in Figure 2 an increase in the sulphur charge is also correlated with an increase in the BDE. However, in this case, we found that most of the  $\text{OH}$  substitutions, the 2,6  $\text{NO}_2$ , 2,4 and 2,6  $\text{CF}_3$  are positioned outside of this distribution pattern. The 2,6  $\text{NO}_2$  substitution is able to withdraw more charge from the sulphur atom than other similar substitutions and this effect moves this substitution to the far right of the plot. Moreover, when compared with the average value for the same substituent, the 2,6  $\text{NO}_2$  molecule is destabilized and the radical is stabilized and both work to lower the BDE by  $20 \text{ kJ mol}^{-1}$  than the average BDE. However, when comparing the same substitution in phenol and thiophenol, the 2,6  $\text{NO}_2$  thiophenol radical is stabilized in comparison to the mean value for same substituents, while the 2,6  $\text{NO}_2$  phenol radical is destabilized. This change is due to the different polarizabilities of oxygen and sulphur.

For thiophenols, the  $\text{OH}$  substitutions in *ortho* positions allow the formation of one or two hydrogen bonds that lowers the BDE by stabilizing the radical. This effect is stronger for 2,6 and 2,4 substitutions.

TABLE I

Selected optimized bond lengths (in disubstituted phenols and thiophenols and respective radicals) and partial NBO charges for oxygen and sulphur in the molecule.

Substituent	Position	Phenols				Thiophenols			
		$d(\text{O—H})$	$d(\text{C—O})$	$d(\text{C—O}^\bullet)$	$q(\text{O})$	$d(\text{S—H})$	$d(\text{C—S})$	$d(\text{C—S}^\bullet)$	$q(\text{S})$
$\text{NH}_2$	2,3	0.974	1.357	1.253	−0.682	1.354	1.796	1.709	−0.021
	2,4	0.969	1.373	1.251	−0.694	1.351	1.806	1.713	−0.020
	2,5	0.975	1.357	1.249	−0.685	1.353	1.799	1.710	−0.013
	2,6	0.973	1.368	1.255	−0.706	1.354	1.799	1.707	−0.028
	3,4	0.962	1.375	1.250	−0.680	1.352	1.803	1.717	−0.015
	3,5	0.962	1.371	1.254	−0.676	1.347	1.790	1.730	0.040
$\text{OH}$	2,3	0.966	1.363	1.253	−0.672	1.347	1.780	1.714	0.043
	2,4	0.965	1.368	1.246	−0.680	1.346	1.786	1.709	0.030
	2,5	0.966	1.362	1.251	−0.671	1.346	1.781	1.711	0.046
	2,6	0.966	1.363	1.257	−0.672	1.352	1.792	1.705	0.003
	3,4	0.962	1.373	1.250	−0.679	1.349	1.798	1.722	0.012
	3,5	0.963	1.367	1.251	−0.671	1.347	1.785	1.727	0.057
$\text{Me}$	2,3	0.962	1.376	1.253	−0.884	1.347	1.793	1.729	0.039
	2,4	0.963	1.375	1.251	−0.683	1.347	1.792	1.722	0.038
	2,5	0.963	1.374	1.250	−0.681	1.347	1.792	1.725	0.041
	2,6	0.962	1.375	1.249	−0.684	1.344	1.796	1.722	0.033
	3,4	0.963	1.373	1.253	−0.678	1.347	1.789	1.725	0.042
	3,5	0.963	1.371	1.253	−0.676	1.347	1.789	1.727	0.046
$\text{Cl}$	2,3	0.967	1.355	1.240	−0.664	1.346	1.779	1.722	0.072
	2,4	0.967	1.356	1.240	−0.665	1.346	1.777	1.718	0.070
	2,5	0.967	1.355	1.240	−0.662	1.346	1.777	1.721	0.076
	2,6	0.967	1.350	1.234	−0.653	1.347	1.775	1.713	0.097
	3,4	0.963	1.365	1.248	−0.666	1.347	1.783	1.725	0.070
	3,5	0.963	1.363	1.249	−0.662	1.347	1.783	1.729	0.077
$\text{CF}_3$	2,3	0.964	1.355	1.246	−0.666	1.348	1.794	1.737	0.107
	2,4	0.965	1.353	1.245	−0.658	1.344	1.778	1.758	0.094
	2,5	0.965	1.356	1.245	−0.661	1.344	1.782	1.731	0.087
	2,6	0.965	1.350	1.240	−0.655	1.343	1.787	1.761	0.100
	3,4	0.964	1.359	1.250	−0.657	1.347	1.777	1.730	0.089
	3,5	0.963	1.361	1.250	−0.659	1.347	1.780	1.730	0.086
$\text{NO}_2$	2,3	0.981	1.344	1.241	−0.643	1.348	1.777	1.736	0.083
	2,4	0.983	1.329	1.238	−0.634	1.348	1.761	1.729	0.120
	2,5	0.981	1.333	1.241	−0.639	1.347	1.769	1.736	0.108
	2,6	0.985	1.323	1.290	−0.620	1.350	1.771	1.726	0.164
	3,4	0.964	1.354	1.246	−0.646	1.348	1.773	1.729	0.112
	3,5	0.964	1.357	1.250	−0.652	1.347	1.778	1.733	0.100
PhXH		0.963	1.370	1.253	−0.675	1.347	1.787	1.728	0.051

The last row corresponds to the unsubstituted parent compound ( $\text{X}=\text{O}, \text{S}$ ). All distances in Å and charges in atomic units.

The calculated O—H and S—H BDEs are presented in Table II. Whenever available, previously published calculated and experimental values are also presented and, as can be seen, a very good agreement

is found between these values and the ones calculated in the present work. Unfortunately there is no experimental or calculated values for di-substituted thiophenols. However, as can be seen in Figure 3, the

TABLE II

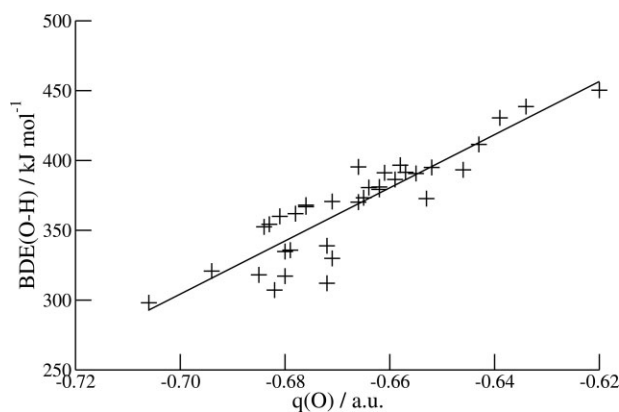
Relative and absolute values for the O–H and S–H bond dissociation enthalpies at 298 K for disubstituted phenols and thiophenols.

Substituent	Position	$\Delta D(\text{O–H})$	BDE(O–H)		$\Delta D(\text{S–H})$	BDE(S–H)
			Calc.	Literature		Calc.
$\text{NH}_2$	2,3	–64.12	307.2		–37.43	312.0
	2,4	–50.53	320.8		–22.16	327.2
	2,5	–53.18	318.1		–32.66	316.7
	2,6	–73.22	298.1	278.1 [19]	–39.82	309.6
	3,4	–36.48	334.8		–20.85	328.5
	3,5	–3.34	368.0		–1.74	347.7
$\text{OH}$	2,3	–32.35	338.9	348.8 [20]; 347.03 [21]	–26.39	323.0
	2,4	–54.08	317.2	311.01 [22]	–44.49	304.9
	2,5	–41.38	329.9		–29.47	319.9
	2,6	–59.24	312.1	327.2 [23]; 308.3 [23]; 318.1 [23]; 312.31 [24]; 324.06 [21]; 327.45 [20]	–47.46	301.9
	3,4	–35.50	335.8		–9.87	339.5
	3,5	–0.68	370.6	369.7 [23]; 375.2 [23]; 370.3 [23]	0.45	349.9
$\text{Me}$	2,3	–10.78	360.5		–2.20	347.2
	2,4	–16.98	354.3	369.25 [19]; 353.5 [24]	–5.34	344.1
	2,5	–11.30	360.0	358.8 [19]	–1.25	348.2
	2,6	–18.77	352.5	357.9 [25]; 355±2 [26]; 353.7 [19]; 353.3 [27]; 356.7 [28]; 353.85 [24]	–3.38	346.0
	3,4	–9.44	361.9		–5.85	343.5
	3,5	–4.37	366.9	364±2 [29]; 368.2 [27]; 367.1 [28]	–2.38	347.0
$\text{Cl}$	2,3	9.28	380.6		10.77	360.2
	2,4	1.98	373.3		5.66	355.1
	2,5	9.67	381.0		10.99	360.4
	2,6	1.36	372.7	368.37 [28]	15.53	364.9
	3,4	–1.14	370.2		0.71	350.1
	3,5	8.03	379.3	393.5 [30]; 388.5 [27]; 382±2 [31]	5.94	355.3
$\text{CF}_3$	2,3	24.08	395.4		15.87	365.3
	2,4	25.25	396.6		36.04	385.4
	2,5	19.94	391.2		14.53	363.9
	2,6	19.38	390.7		31.83	381.2
	3,4	20.22	391.5		12.30	361.7
	3,5	15.12	386.4		9.37	358.8
$\text{NO}_2$	2,3	40.16	411.5		19.98	369.4
	2,4	67.35	438.6		10.25	359.6
	2,5	59.23	430.5		11.35	360.7
	2,6	79.01	450.3		–10.71	338.7
	3,4	21.95	393.3		14.84	364.2
	3,5	23.73	395.0		14.53	363.9

The calculated absolute bond dissociation enthalpies were obtained by using the recommended value of dos Santos and Simões [12] for phenol (371.3 kJ mol<sup>–1</sup>) and the value of dos Santos et al. [32] for thiophenol (349.4 kJ mol<sup>–1</sup>). All energies in kJ mol<sup>–1</sup>.  $\Delta D(\text{X–H}) = (\text{BDE}_{\text{ARX–H}} - \text{BDE}_{\text{PhX–H}})$ .

Hammett sigma parameters [33] correlate very well with our calculated BDEs. This is even more notorious since the series studied is about disubstituted

thiophenols and, consequently, the error in the correlation between the Hammett sigma parameters and BDEs is also doubled.

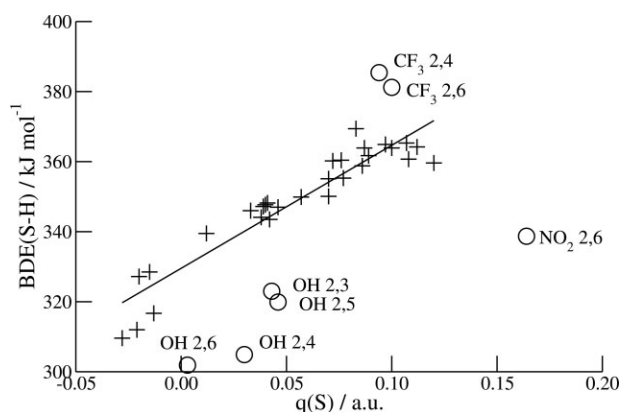


**FIGURE 1.** Correlation between calculated BDEs of disubstituted phenols and phenolic oxygen NBO charges. The straight line corresponds to the best fit ( $r = 0.895$ ) to all values but the 2,3 CH<sub>3</sub> (not displayed).

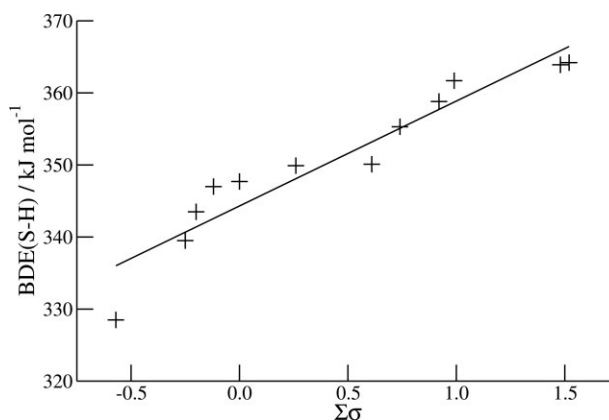
Except for NH<sub>2</sub>, in general the BDEs for thiophenols are always lower than the respective phenol ones.

The value in the lower left part of Figure 3 is the one that is further away from the fitting line. This value corresponds to a 3,4 NH<sub>2</sub> substitution. If we compare this substitution with a similar one at position 3,5 (which is much closer to the fitting line) one can see that the major contribution to the BDE energy difference between both (about 19 kJ mol<sup>-1</sup>) is due to the higher stabilization of the 3,4 radical (about 15 kJ mol<sup>-1</sup>).

In Figure 4 the correlation between the Hammett sigma parameters and the phenol BDEs is



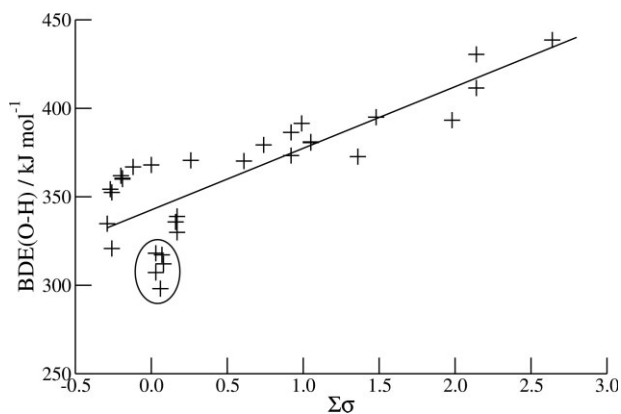
**FIGURE 2.** Correlation between calculated BDEs of disubstituted thiophenols and thiophenolic sulphur NBO charges. The straight line corresponds to the best fit to all values but the ones represented by circles ( $r = 0.942$ ).



**FIGURE 3.** Correlation between calculated BDEs of disubstituted thiophenols and Hammett sigma parameters. The straight line corresponds to the best fit to all values ( $r = 0.949$ ).

displayed. The values that present the lowest BDEs are also the ones that most deviate from the fitting line. These values are, in an increasing BDE order: 2,6 NH<sub>2</sub>, 2,3 NH<sub>2</sub>, 2,6 OH, 2,4 OH, and 2,5 NH<sub>2</sub>.

The 2,6 OH radical is specially stable. It is 31 kJ mol<sup>-1</sup> more stable than the average value of all radicals of this substitution type. This value decreases to 17 kJ mol<sup>-1</sup> for the 2,4 substitution. For the other three NH<sub>2</sub> substitutions, the 2,6 radical is 29 kJ mol<sup>-1</sup> more stable than the average value, the 2,3 19 kJ mol<sup>-1</sup> and the 2,5 is only 8 kJ mol<sup>-1</sup> more stable. The stabilization of these radicals is the major factor for their different behavior.



**FIGURE 4.** Correlation between calculated BDEs of disubstituted phenols and Hammett sigma parameters. The straight line corresponds to the best fit to all values ( $r = 0.842$ ). In an increasing BDE order, the encircled values correspond to the 2,6 NH<sub>2</sub>, 2,3 NH<sub>2</sub>, 2,6 OH, 2,4 OH, and 2,5 NH<sub>2</sub> substitutions.

## 4. Conclusions

With the present work we have explored the energetics and geometries of disubstituted phenol and thiophenol molecules using density functional theory. Our structural and energetic data are in very good agreement with previous calculated and experimental results.

Two major groups could be drawn based on their ability to reduce or increase the relative BDE (the comparison is made with the respective dissociation bond energies of phenol or thiophenol:  $\Delta D(X-H) = BDE_{ARX-H} - BDE_{PhX-H}$ ;  $X=O, S$ ) of  $X-H$ . In one group we have methyl, hydroxide, amino, and on the other, trifluoromethyl, chloride, and nitro substituents. The first group reduces and the second increases the dissociation energy of the homolytic  $X-H$  bond cleavage. For each group, a rank could be established. For the first group,  $NH_2 > OH > CH_3$  and in the other group,  $NO_2 > CF_3 > Cl$ . This group division is clearly correlated with the ability for the additions to withdraw (decreases the BDE) or donate electrons (increases the BDE).

It was found that the substituents can increase the O-H bond length (this effect decreases in the following order:  $NO_2 > NH_2 > Cl > OH > CF_3 > CH_3$ ) while also decreasing the C-O bond length ( $NO_2 > NH_2 > Cl > CF_3 > OH (> CH_3)$ ). The  $CH_3$  has almost no effect on the C-O bond length. The substituents can also decrease the oxygen atom charge ( $NO_2 > Cl > CF_3 > CH_3 > OH > NH_2$ ) which is clearly correlated with the substituent ability to withdraw or donate electrons.

Although the absolute BDE of phenol is larger than the absolute BDE of thiophenol, also the effect of the same addition on the BDE is, in general, larger in phenol than in thiophenol ( $\Delta D(X-H)$ ;  $X=O, S$ ). For Cl and  $CF_3$  in the 2,6 substitutions, the relative change in the BDE is larger in thiophenols.

Good correlations between the charge or sigma Hammett parameters and the BDEs values were found. The substitutions that deviate from the Hammett correlation could be explained based on the stabilization of the respective radicals.

## References

- Nam, P. C.; Nguyen, M. T.; Chandra, A. K. 2006, 110, 10904.
- Mulder, P.; Korth, H.-G.; Ingold, K. U. *Helv Chim Acta* 2005, 88, 370.
- Black, H. S. *Integr Cancer Ther* 2004, 3, 279.
- Maritim, A. C.; Sanders, R. A.; Watkins, J. B., III. *J Biochem Mol Toxicol* 2003, 17, 24.
- Berlett, B. S.; Stadtman, E. R. *J Biol Chem* 1997, 272, 20313.
- Schöneich, C. *Exp Gerontol* 1999, 34, 19.
- Surdhar, P. S.; Armstrong, D. A. 1987, 91, 6532.
- Dey, G. R.; Naik, D. B.; Kishore, K.; Moorthy, P. N. *Rad Phys Chem* 1999, 54, 19.
- Tobien, T.; Cooper, W. J.; Nickelsen, M. G.; Pernas, E.; O'Shea, K. E.; Asmus, K.-D. *Environ Sci Technol* 2000, 34, 1286.
- Fu, Y.; Lin, B.-L.; Song, K.-S.; Liu, L.; Guo, Q.-X. *J Chem Soc Perkin Trans* 2002, 2, 1223.
- da Silva, M. A. V. R.; Matos, M. A. R.; Miranda, M. S.; Sousa, M. H. F. A.; dos Santos, R. M. B.; Bizarro, M. M.; Simões, J. A. M. *Struct Chem* 2001, 12, 171.
- dos Santos, R. M. B.; Simões, J. A. M. *J Phys Chem Ref Data* 1998, 27, 707.
- Jackson, R. A.; Hosseini, K. M. *J Chem Soc Commun* 1992, 967.
- Bordwell, F. G.; Zhang, X.-M.; Satish, A. V.; Cheng, J.-P. *J Am Chem Soc* 1994, 116, 6605.
- Becke, A. D. *J Chem Phys* 1993, 98, 5648.
- Klein, E.; Lukeš, V. *Chem Phys* 2006, 330, 515.
- Ditchfield, R.; Hehre, W. J.; Pople, J. A. *J Chem Phys* 1971, 54, 724.
- Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Montgomery, J. A., Jr.; Vreven, T.; Kudin, K. N.; Burant, J. C.; Millam, J. M.; Iyengar, S. S.; Tomasi, J.; Barone, V.; Mennucci, B.; Cossi, M.; Scalmani, G.; Rega, N.; Petersson, G. A.; Nakatsuji, H.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Klene, M.; Li, X.; Knox, J. E.; Hratchian, H. P.; Cross, J. B.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Ayala, P. Y.; Morokuma, K.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Zakrzewski, V. G.; Dapprich, S.; Daniels, A. D.; Strain, M. C.; Farkas, O.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Ortiz, J. V.; Cui, Q.; Baboul, A. G.; Clifford, S.; Cioslowski, J.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Gonzalez, C.; Pople, J. A. *Gaussian 03, Revision C.2*. Gaussian and Inc. Pittsburgh PA, 2003.
- Wright, J. S.; Carpenter, D. J.; McKay, D. J.; Ingold, K. U. *J Am Chem Soc* 1997, 119, 4245.
- Ji, H.-F.; Zhang, H.-Y. *New J Chem* 2005, 29, 535.
- Bakalbassis, E. G.; Lithoxidou, A. T.; Vafiadis, A. P. 2003, 107, 8594.
- Zhang, H.-Y.; Sun, Y.-M.; Wang, X.-L. *Chem Eur J* 2003, 9, 502.
- Correia, C. F.; Guedes, R. C.; dos Santos, R. M. B.; Cabral, B. J. C.; Simões, J. A. M. *Phys Chem Chem Phys* 2004, 6, 2109.
- Wright, J. S.; Johnson, E. R.; DiLabio, G. A. *J Am Chem Soc* 2001, 123, 1173.
- Mahoney, L. R.; DaRooge, M. A. *J Am Chem Soc* 1975, 97, 4722.
- Lucarini, M.; Pedrielli, P.; Pedulli, G. F.; Cabiddu, S.; Fattuoni, C. *J Org Chem* 1996, 61, 9259.



27. Bordwell, F. G.; Cheng, J.-P. *J Am Chem Soc* 1991, 113, 1736.
28. Brigati, G.; Lucarini, M.; Mugnaini, V.; Pedulli, G. F. *J Org Chem* 2002, 67, 4828.
29. Lucarini, M.; Mugnaini, V.; Pedulli, G. F. *Struct Chem* 2003, 14, 399.
30. Nielsen, M. F.; Ingold, K. U. *J Am Chem Soc* 2006, 128, 1172.
31. Arnett, E. M.; Amarnath, K.; Harvey, N. G.; Venimadhavan, S. *J Am Chem Soc* 1990, 112, 7346.
32. dos Santos, R. M. B.; Muralha, V. S. F.; Correia, C. F.; Guedes, R. C.; Cabral, B. J. C.; Simões, J. A. M. *J Phys Chem A* 2002, 106, 9883.
33. Perrin, D. D.; Dempsey, B.; Serjeant, E. P. *pK<sub>a</sub> Prediction for Organic Acids and Bases*; Chapman and Hall: London, 1981.