

## Substituted Phenyl 2-Thiophenecarboxylates and Benzoates: Synthesis, NMR Spectra, and Aromaticity Index

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A series of *m*- and *p*-substituted phenyl 2-thiophenecarboxylates and benzoates was prepared by the reaction of the corresponding acyl chlorides and phenols. Their  $^1\text{H}$  and  $^{13}\text{C}$  NMR chemical shifts were analyzed using single substituent parameter (SSP) and dual substituent parameter (DSP) methods. The relative aromaticity index of thiophene was estimated to be 0.92 from the plot of the chemical shift of the carbonyl carbons of the thienoyl esters against chemical shift of the carbonyl carbons of the benzoyl esters.

### Introduction

The aromaticity of 5-membered heterocyclic compounds has been of interest to many chemists because these compounds are the basic structural moiety of many natural products that possess a wide spectrum of biological activities. Although these compounds meet the requirement of Huckel's rule of aromaticity, possessing  $6\pi$  electrons in a planar cyclic arrangement of ring-forming atoms, they are believed to be less aromatic than benzene.<sup>1</sup> For example, in a comparison of the indices of aromaticity, with that of benzene set as 1, the values of 0.46, 0.59, and 0.75 are assigned to furan, pyrrole, and thiophene, respectively. These values are calculated by the ring currents measured by the chemical shifts of the protons.<sup>2</sup>

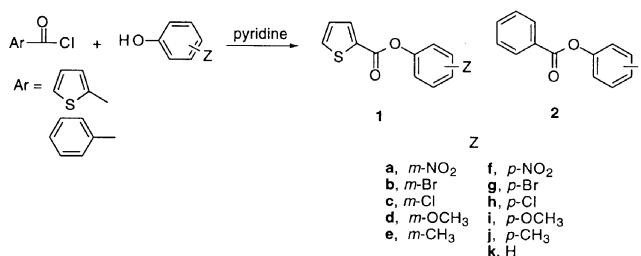
In contrast, the aromaticity indices derived from the bond length and the number of  $\pi$  electrons in the ring are very close in value: benzene, 1; thiophene, 0.93; pyrrole, 0.91; furan, 0.87.<sup>3</sup> Among thiophene, pyrrole, and furan, which are commonly encountered as 5-membered heterocycles, thiophene is considered most similar to benzene, and the relative aromaticity of thiophene ranges from 0.55 to 0.93, when the aromaticity of benzene is set at 1. Recently, a new order of values with benzene set at 100 was reported for furan (53), thiophene (81.5), and pyrrole (85).<sup>4</sup> It is not certain why the order between pyrrole and thiophene switched.

Our continuous study on the aromaticities of five-membered heterocyclic compounds<sup>5,6</sup> led us to the preparation of *m*- and *p*-substituted phenyl esters of 2-thiophenecarboxylic acid (2-thienoate) to examine the effect of the substituents on the phenyl ring on the chemical shift of the H and C atoms of the thiophene ring.

### Results and Discussion

The substituted phenyl 2-thienoates (**1a-k**) were prepared by the reactions of 2-thienoyl chloride with *m*- and *p*-substituted phenols in pyridine.<sup>6</sup> Similarly, the substituted phenyl benzoates (**2a-k**) were prepared for comparison. The benzoates are reported in literature, except **2d**. The melting points of benzoates are consistent with the reported values, except **2g**. The esters were purified by recrystallization or

chromatography to obtain an analytical purity, which is essential to the preparation of the 0.1 M solution in chloroform-*d* for NMR measurement.



The  $^1\text{H}$  and  $^{13}\text{C}$  NMR chemical shift values are listed in Tables 1 and 2, respectively. The averaged values of the  $^1\text{H}$  chemical shift of the thienoates (**1**) are  $\delta$  7.98, 7.18, and 7.68 for 3-, 4-, and 5-H, respectively. If the thiophene ring is considered an analogue of the benzene ring, they are *ortho*-, *meta*-, and *para*-H from the carbonyl group, respectively. The benzoates (**2**) show the values  $\delta$  8.20, 7.52, and 7.65 for *o*-, *m*-, and *p*-H, respectively. If we use a value of  $\delta$  7.26 for proton in the benzene ring and the respective values of  $\delta$  7.20 and 6.96 for 2,5-H and 3,4-H of the thiophene ring,<sup>7</sup> the averaged correction values of Z-C<sub>6</sub>H<sub>4</sub>OC=O from our investigation indicate that the magnitude of the down-field shift is greater in the case of *o*- and *p*-H of the thienoyl protons than for the benzoyl protons. They are *o*-H (1.02 ppm), *m*-H (0.22 ppm), and *p*-H (0.48 ppm) for 2-thienoyl ring, whereas the corresponding values of 0.94 ppm, 0.26 ppm, and 0.39 ppm were observed for the benzoyl ring.

It is noteworthy that the substituent correction of CH<sub>3</sub>OC=O group for the  $^1\text{H}$  chemical shift values of a phenyl ring and a 2-thienyl ring are very close.<sup>7</sup> They are *o*-H (0.71), *m*-H (0.11), and *p*-H (0.21) of a phenyl ring, and *o*-H (0.70), *m*-H (-0.05), and *p*-H (0.20) for a 2-thienyl ring. Therefore, the phenyl ester causes more down-field shift than the methyl ester.

In contrast with  $^1\text{H}$ , the averaged values of the  $^{13}\text{C}$  chemical shift show the opposite trend as well as similarities. For example, the *i*- and *o*-C signals of the thienoates (**1**) appear at 132.49 ppm and 134.89 ppm, whereas those of the benzoates (**2**) show at 129.25 ppm and 130.74 ppm. On the

**Table 1.**  $^1\text{H}$  Chemical shift values of aryl 2-thiophenecarboxylates (**1**) and aryl benzoates (**2**)

Comp	3-H	4-H	5-H	2'-H	3'-H	4'-H	5'-H	6'-H
1a	8.02	7.22	7.73	8.15		8.16	7.61	7.60
2a	8.21	7.55	7.69	8.04		8.14	7.62	7.61
1b	7.98	7.18	7.68	7.42		7.41	7.29	7.18
2b	8.19	7.52	7.65	7.43		7.42	7.30	7.18
1c	7.98	7.18	7.68	7.27		7.26	7.35	7.14
2c	8.19	7.52	7.65	7.27		7.26	7.36	7.14
1d	7.98	7.18	7.66	6.78		6.82	7.31	6.82
2d	8.20	7.51	7.64	6.78		6.82	7.32	6.83
1e	7.97	7.17	7.65	7.04		7.08	7.30	7.02
2e	8.20	7.51	7.63	7.03		7.08	7.31	7.02
1f	8.02	7.22	7.74	7.43	8.32			
2f	8.21	7.55	7.69	7.43	8.33			
1g	7.98	7.18	7.68	7.12	7.53			
2g	8.19	7.52	7.65	7.12	7.54			
1h	7.98	7.18	7.68	7.17	7.38			
2h	8.19	7.52	7.65	7.17	7.39			
1i	7.97	7.17	7.65	7.13	6.93			
2i	8.20	7.50	7.63	7.13	6.94			
1j	7.97	7.17	7.65	7.09	7.21			
2j	8.20	7.50	7.63	7.09	7.22			
1k	7.98	7.18	7.66	7.22	7.42	7.27		
2k	8.21	7.51	7.64	7.22	7.43	7.27		

other hand, *m*- and *p*-Cs of **1** and **2** show very similar values: 128.60 ppm and 133.74 ppm for **1** and 128.08 ppm and 133.76 ppm for **2**.

The down-field shift of the  $^{13}\text{C}$  signal is more remarkable

in the 2-thiophenyl ring. The peaks corresponding to the  $\alpha$ - and  $\beta$ -C of thiophene appear at 125.6 ppm and 127.3 ppm.<sup>8</sup> The averaged deviation for the esters **1** from the values are *i*-C (6.89 ppm), *o*-C (7.59 ppm), *m*-C (1.30 ppm), and *p*-C (8.16 ppm). Similar calculations for the benzoate esters **2** show *i*-C (0.75 ppm), *o*-C (1.68 ppm), *m*-C (0.10 ppm), and *p*-C (5.25 ppm). These results indicate that the electronic environment of the thiophenyl ring is more influenced by the substituent,  $\text{Z-C}_6\text{H}_4\text{OC=O}$  than the phenyl ring.

The transmission of the effect of a substituent has been widely studied using  $^{13}\text{C}$  NMR spectroscopy. The substituent chemical shift (SCS) may be represented by eqs. (1) and (2).<sup>9</sup>

$$\delta_i = \rho_i \sigma_i + \delta_o \quad (1)$$

$$\delta_i = \rho_i \sigma_{Ri} + \rho_R \sigma_{Ri} + \delta_o \quad (2)$$

The closely related systems to the present research are the 2-(*m*- and *p*-substituted)phenylfuran<sup>10</sup> and *p*-substituted benzophenone.<sup>11-13</sup> The former system has the structural characteristics of the furan ring, being directly bonded to a substituted benzene ring, facilitating the transmission of the SCS to the carbon atoms of the furan ring. In contrast, the latter system has an insulating carbonyl moiety between the two benzene rings so that only minor direct conjugation is possible.

To obtain useful comparison between the 2-(*p*-substituted phenyl)furan in the literature<sup>10</sup> and the present system, it is particularly instructive to analyze the data listed in Table 2 by both the single substituent parameter (SSP) and dual substituent parameter (DSP) treatments shown in eqs. (1) and

**Table 2.**  $^{13}\text{C}$  Chemical shift values of aryl 2-thiophenecarboxylates (**1**) and aryl benzoates (**2**)

	C=O	2-C	3-C	4-C	5-C	1'-C	2'-C	3'-C	4'-C	5'-C	6'-C
1a	159.85	131.63	135.43	128.28	134.42	150.80	117.48	148.79	120.91	130.07	128.16
2a	164.54	128.52	130.29	128.67	134.18	151.23	117.56	148.84	120.84	130.08	128.25
1b	160.12	132.27	134.99	128.12	133.88	151.01	125.18	122.40	129.17	130.49	120.55
2b	164.76	129.05	130.20	128.64	133.84	151.43	125.18	122.43	129.08	130.51	120.62
1c	160.14	132.30	134.99	128.12	133.88	150.98	122.35	134.73	126.27	130.18	120.06
2c	164.76	129.07	130.20	128.63	133.83	151.40	122.43	134.75	126.18	130.20	120.13
1d	160.50	132.86	134.75	128.01	133.49	151.48	107.55	160.50	111.99	129.83	113.82
2d	165.08	129.52	130.15	128.55	133.57	151.90	107.64	160.53	111.84	129.85	113.89
1e	160.68	133.00	134.58	127.97	133.48	150.49	122.21	139.66	126.77	129.17	118.56
2e	165.29	129.63	130.13	128.53	133.51	150.88	122.28	139.67	126.68	129.19	118.62
1f	159.52	131.66	135.50	128.32	134.52	155.26	122.51	125.25	145.41		
2f	164.22	128.50	130.31	128.78	134.24	155.70	122.62	125.26	145.38		
1g	160.22	132.38	134.93	128.10	133.80	149.56	123.45	132.49	119.07		
2g	164.85	129.14	130.18	128.62	133.79	149.95	123.53	132.51	118.97		
1h	160.30	132.41	134.90	128.09	133.78	148.99	123.02	129.50	131.35		
2h	164.93	129.16	130.18	128.62	133.78	149.40	123.09	129.53	131.26		
1i	160.96	132.96	134.54	127.91	133.33	144.04	122.40	114.47	157.35		
2i	165.53	129.62	130.11	128.52	133.58	144.39	122.42	114.50	157.29		
1j	160.79	133.02	134.55	127.96	133.32	148.32	121.29	129.96	135.62		
2j	165.37	129.67	130.13	128.51	133.47	148.69	121.35	129.98	135.49		
1k	160.58	132.90	134.66	128.00	133.46	150.56	121.64	129.46	125.97		
2k	165.18	129.57	130.16	128.55	133.57	150.94	121.70	129.48	125.87		

(2), respectively. It should provide an example of the relative merits of the single and dual substituent parameter scales for the comparison of the interpretation of substituent-induced chemical shifts.<sup>9,14,15</sup>

Table 3 lists the results of the SSP calculation for the series of **1** and **2**. The "goodness of fit" of an SSP or DSP correlation is usually judged by the parameter  $f$  ( $-SD/RMS$ ; where  $SD$  stands for the standard deviation of the fit, and  $RMS$  is the root-mean-square size of the experimental data). The smaller the  $f$  value, the better the fit.  $f$  values of 0.0-0.1 represent excellent correlation, and  $f$  values of 0.1-0.2 represent moderately good correlation.  $f$  values greater than 0.3 may be considered only as a crude trend.<sup>16</sup>

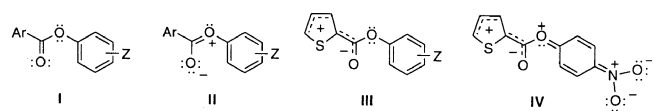
As shown in Table 3, the SSP treatments show only moderate correlation for the  $^{13}\text{C}$  chemical shift of the ring and the carbonyl carbons for **1** and **2**. However, it should be pointed out that the thienyl carbons show better correlation than the benzoyl carbon. The correlation coefficient alone may be used as a base to judge the fit. Such consideration also confirms that the thienoates (**1**) show better correlation ( $r = 0.971$ - $0.990$ ) than the benzoates (**2**,  $r = 0.954$ - $0.987$ ). There are a few striking facts in the correlation of the chemical shifts. First of all, the carbonyl and the  $i$ -Cs show inverse substituent effects, while the  $o$ -,  $m$ -, and  $p$ -Cs show normal effects. Secondly, the magnitude of the  $\rho$  values of **1** are greater than those of **2**, especially, the  $o$ -C of **1** is about five

times larger than that of **2**. Thirdly, the chemical shift values of  $^{13}\text{C}$  of both **1** and **2** do not show any correlation with  $\sigma$ . This seems quite unusual because there are ample reports of good correlation of  $^{13}\text{C}$  for other systems such as  $p$ -substituted benzophenones<sup>11,12</sup> and  $p$ -substituted styrenes.<sup>14</sup> The similarities in  $\rho$ ,  $r$ , and  $f$  values of  $^{13}\text{C}$  between **1** and **2** are even more striking. This observation may indicate that the effects of the thienoyl and the benzoyl groups on the electron densities of  $^{13}\text{C}$  are very similar.

These points become clearer as we examine the DSP analysis data in Table 4. The  $\rho_R$  was obtained by using  $\sigma_R(\Lambda)$  values. In general, four sets of  $\sigma_R$  values are considered for DSP analysis, and they are  $\sigma_R^0$ ,  $\sigma_R^0(\text{BA})$ ,  $\sigma_R(\Lambda)$ , and  $\sigma_R^1$ .<sup>16</sup>  $\sigma_R(\Lambda)$  was derived from the ionization of anilinium ion in water at 25 °C.



The fact that the best fit for **1** and **2** was obtained with  $\sigma_R(\Lambda)$  may be evidence of a significant contribution of the resonance structure like II.



**Table 3.** Best fit of the SSP equation for the  $^{13}\text{C}$  chemical shifts in **1** and **2**

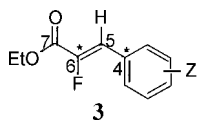
	<b>1</b>					<b>2</b>					
	$\rho$	$\delta_0$	$r$	SD	$f$	$\rho$	$\delta_0$	$r$	SD	$f$	$\rho_2/\rho_1$
C=O	-1.25	160.59	0.989	0.06	0.13	-1.13	165.19	0.987	0.06	0.14	0.90
$i$ -C	-1.47	132.80	0.971	0.12	0.18	-1.24	129.50	0.975	0.09	0.17	0.84
$o$ -C	0.97	134.69	0.986	0.05	0.13	0.19	130.15	0.977	0.01	0.19	0.20
$m$ -C	0.38	128.00	0.990	0.02	0.12	0.23	128.56	0.954	0.02	0.25	0.60
$p$ -C	1.19	133.51	0.981	0.09	0.15	0.74	133.61	0.958	0.07	0.23	0.62
$^{13}\text{C}$	6.01	148.89	0.749	1.70	0.65	6.08	149.27	0.751	1.71	0.65	1.01

**Table 4.** Best fit of the DSP equation for the  $^{13}\text{C}$  chemical shifts in **1** and **2**

	para-1						para-2					
	$\rho_I$	$\rho_R$	$\delta_0$	SD	$f$	$\lambda$	$\rho_I$	$\rho_R$	$\delta_0$	SD	$f$	$\lambda$
C=O	-1.2	-1.0	160.50	0.10	0.19	0.83	-1.1	-0.9	165.10	0.09	0.20	0.82
$i$ -C	-1.4	-0.8	132.90	0.04	0.07	0.57	-1.1	-0.8	132.90	0.04	0.08	0.73
$o$ -C	0.7	0.8	134.61	0.04	0.10	1.14	0.15	0.15	130.16	0.01	0.09	1.00
$m$ -C	0.3	0.3	128.00	0.02	0.13	1.00	0.2	0.2	128.55	0.01	0.10	1.00
$p$ -C	1.0	0.9	133.44	0.03	0.07	0.90	0.6	0.6	133.52	0.05	0.15	1.00
$^{13}\text{C}$	-2.0	13.4	150.99	1.28	0.89	-6.70	-2.1	13.3	150.95	1.29	0.89	-6.33
	meta-1						meta-2					
	$\rho_I$	$\rho_R$	$\delta_0$	SD	$f$	$\lambda$	$\rho_I$	$\rho_R$	$\delta_0$	SD	$f$	$\lambda$
C=O	-1.0	-0.3	160.56	0.06	0.16	0.30	-1.0	-0.2	165.21	0.05	0.12	0.20
$i$ -C	-1.6	-0.6	132.89	0.05	0.08	0.38	-1.2	-0.6	129.60	0.05	0.09	0.50
$o$ -C	1.0	0.3	134.69	0.02	0.06	0.30	0.2	0.05	130.16	0.01	0.24	0.25
$m$ -C	0.3	0.2	127.99	0.01	0.09	0.67	0.2	0.05	128.56	0.02	0.23	0.25
$p$ -C	1.0	0.6	133.39	0.05	0.10	0.60	0.8	0.3	133.59	0.03	0.09	0.38
$^{13}\text{C}$	1.3	-1.2	150.40	0.18	0.75	-0.92	1.2	-1.3	150.72	0.19	0.84	-1.08

The positively charged oxygen atom bonded to the phenyl ring may be considered an analogue of the nitrogen atom in the anilinium ion.

The structure II may, in turn, be considered a stilbene or a substituted styrene. There are ample examples of correlation of  $^{13}\text{C}$  of styrene with DSP. But the pattern of the normal and inverse effect shown in the styrene system are absent from the present system.<sup>9</sup> For example, C-4 and C-6 (marked with \*) of ethyl  $\alpha$ -fluorocinnamates (**3**) show normal substituent effect, while C-5 and C-7 show inverse effect.<sup>17</sup> That is, the normal and inverse effects alternate in the styrene system. In contrast, the carbonyl and *i*-carbons of **1** and **2** show inverse effect, while *o*-, *m*-, and *p*-Cs show normal effect.



The  $\lambda$  value, which is the ratio of  $\rho_R/\rho_I$ , also presents interesting comparisons. For the cinnamate the  $\lambda$  values are 0.65, 2.27, and 1.09 for C-5, C-6, and C-7, respectively, for the *p*-substituted series of **3**.<sup>17</sup> This means that the relative contribution of  $\rho_R$  varies significantly depending upon the position. The esters **1** and **2**, however, show a relatively narrow range of  $\lambda$  values. In the case of the *p*-substituted phenyl ester series the values are essentially 1 for *o*-, *m*-, and *p*-Cs of **1** and **2**.

It should also be pointed out that the  $\rho_I$  values are larger than the  $\rho_R$  values for all the carbons of thienoyl and benzoyl rings regardless of the positions in the ring. This should be evidence that conjugation through a structure like II is not as effective as it is in a styrene system.

The inverse effect of the substituent may be explained by the  $\pi$  polarization shown in structure III. The polarization of the carbonyl group induced by the electron-withdrawing substituent Z (like structure IV) results in an increase in  $\pi$  electron density at carbonyl and *i*-carbons. An increase in electron density may correspond to an up-field chemical shift, which, in turn, may be reflected as negative  $\rho_I$ . On the other hand, *o*-, *m*-, and *p*-Cs may show normal effect, according to the structure III. Unlike the styrene, in which the effect alternates, the present system is the first example to be reported in which a block of carbon atoms in a structure shows either normal or inverse effect. In the cases of *m*-substituted series, the  $\rho_I$  values are significantly larger than the  $\rho_R$  values. The distance of the substituent may be the principal factor for  $\rho_I$ .

The slope of a plot of the chemical shift of any thienyl carbon vs. that of benzoyl carbon may be a measure of the relative aromaticity of thiophene. Table 5 lists the values of the slopes of such plots. The slope corresponding to carbonyl carbon, which is 0.92 should be an acceptable value for the relative index of aromaticity of the thiophene. The combination of the smallest value of the slope of *o*-C (0.191) with an excellent correlation coefficient (0.992) is very unusual. Furthermore, *o*-Hs do not show any meaningful correlation ( $r = 0.529$ ). The observation may be explained by an interaction

**Table 5.** Slopes and correlation coefficients (in parenthesis) of the plots of  $^1\text{H}$  and  $^{13}\text{C}$  chemical shift values of the phenyl ring vs. those of 2-thiophenecarboxylates in chloroform-*d* (0.1 M)

Position	Slope ( $r$ )	Position	Slope ( $r$ )
-		C=O	0.920 (0.999)
-		<i>i</i> -C	0.836 (0.999)
<i>o</i> -H	0.270 (0.529)	<i>o</i> -C	0.191 (0.992)
<i>m</i> -H	0.869 (0.999)	<i>m</i> -C	0.604 (0.963)
<i>p</i> -H	0.695 (0.999)	<i>p</i> -C	0.636 (0.990)
-		1'-C	1.008 (0.999)
2'-H	0.919 (0.999)	2'-C	0.998 (0.999)
3'-H	0.996 (1.000)	3'-C	1.000 (1.000)
4'-H	0.980 (0.999)	4'-C	1.002 (1.000)
5'-H	0.981 (0.999)	5'-C	0.995 (0.999)
6'-H	0.999 (0.999)	6'-C	1.002 (1.000)

between *o*-H and the phenoxy oxygen atom. The distance between benzoyl-*o*-H and phenoxy oxygen atom (2.538 Å) is shorter than that of the thienyl-*o*-H and phenoxy oxygen (2.612 Å). Therefore, the degree of transmission of the effect of substituent through space may be different.

The magnitudes of the slopes of 3'-, 4'-, 5'- and 6'-H are close to 1, whereas the magnitude of 2'-H is 0.919. This may also be due to the interaction between 2'-H and the oxygen atom of the carbonyl group. The degree of such effect should be different between **1** and **2**. The magnitudes of the slopes of 1'-C - 6'-C, which are essentially 1, may be an indication of the fact that the electronic effects of 2-thienoyl and benzoyl groups are effectively blocked from being transmitted to the phenyl ring by the oxygen atom of the phenoxy group.

There are four conformations possible for **1**, such as V, VI, VII, and VIII. On the other hand, two conformations, IX and X, may represent the possible arrangement of the two benzene rings in space. The conformation V is the most stable and VIII is the least stable, according to the calculation by PCMODEL program. The calculation also shows that the thienyl and phenyl rings are essentially coplanar in V and that two phenyl rings in IX are also coplanar. However, it is reasonable to assume that the conformation in the gas phase may not be applicable to solutions in which the solute-solute and solute-solvent interaction varies depending on the concentration.

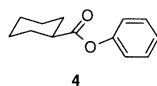
To examine the effect of concentration on chemical shift, we examined the chemical shift of H and C atoms of **1k** and **2k** at the molar concentrations of 0.01, 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0, and the results are listed in Table 6. First of all, the chemical shift and the concentration show excellent correlation ( $r = 0.999$ ). Secondly, the chemical shifts of all the H and C atoms move to upfield as the concentration increases. Thirdly, the magnitude of the slope of thienyl-H of **1k** is larger than the magnitude of the corresponding benzoyl-H of **2k**. On the other hand, the magnitude of the slopes of the phenyl-H of **2k** is slightly larger than those of the corresponding phenyl-H of **1k**. In case of  $^{13}\text{C}$  the values of the magnitude of the slope of four benzoyl carbons are close (-10.98 to -12.93), whereas those of four thienoyl carbons

**Table 6.** Slopes (in Hz) and correlation coefficients (in parenthesis) of the plots of  $^1\text{H}$  and  $^{13}\text{C}$  chemical shift values of **1k**, **2k**, and phenyl cyclohexanecarboxylate (**4**) vs. concentrations

	<b>1k</b>		<b>2k</b>		<b>2k/1k</b>	<b>4</b>		
	slope	<i>r</i>	slope	<i>r</i>		slope	<i>r</i>	
<i>o</i> -H	-14.29	0.999	-8.93	0.999	0.63	1-H	-7.70	0.999
<i>m</i> -H	-24.34	0.999	-21.45	0.999	0.88	2 $\alpha$ -H	-8.65	0.998
<i>p</i> -H	-27.24	0.999	-22.78	0.999	0.84	2 $\beta$ -H	-6.63	0.998
						3-H	-7.18	0.991
						4-H	-4.10	0.997
<i>o'</i> -H	-7.70	0.999	-8.16	0.999	1.06	<i>o'</i> -H	-6.26	0.969
<i>m'</i> -H	-14.89	0.999	-16.16	0.999	1.14	<i>m'</i> -H	-11.24	0.999
<i>p'</i> -H	-14.03	0.999	-15.92	0.969	1.13	<i>p'</i> -H	-11.69	0.999
<i>i</i> -C	-17.16	0.991	-11.74	0.999	0.68	1-C	-14.31	0.999
<i>o</i> -C	-12.76	0.998	-12.93	0.999	1.01	2-C	-11.43	0.999
<i>m</i> -C	-9.50	0.999	-10.98	0.999	1.16	3-C	-12.26	0.999
<i>p</i> -C	-7.37	0.999	-11.38	0.999	1.54	4-C	-10.66	0.999
<i>i'</i> -C	-13.41	0.982	-9.12	0.999	0.68	<i>i'</i> -C	-9.20	0.999
<i>o'</i> -C	-11.16	0.999	-9.87	0.999	0.88	<i>o'</i> -C	-11.89	0.999
<i>m'</i> -C	-11.57	0.999	-11.39	0.999	0.98	<i>m'</i> -C	-12.77	0.999
<i>p'</i> -C	-12.09	0.999	-12.18	0.999	1.01	<i>p'</i> -C	-12.97	0.999
C-O	-15.84	0.999	-16.51	0.999	1.04	C-O	-19.18	0.997

vary widely (-7.37 to -17.16).

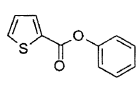
To examine the possible stacking between the aryl rings as a cause of the observed linearity, the NMR spectra of phenyl cyclohexanecarboxylate (**4**) were obtained at the same con-

**4**

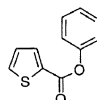
centrations, and the slopes are listed in Table 6.

In **4**, the magnitude of the slope of *o'*-H is the smallest, while that of C-O is the largest. Although the magnitudes of the slopes vary to some extent, they seem to show only those changes due to solvent-solute interaction and not to solute-solute interaction, like stacking. The smallest magnitude of the slope of *o*-H and *o'*-H in **1k**, **2k**, and **4** may be due to the significant influence of the oxygen atom, like XI and XII, which is consistent with the observation of no correlation shown in Table 5.

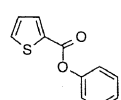
Although the nature of such interaction cannot be specified, the line broadening of the signal corresponding to the *o'*-H compared with those of *m'*- and *p'*-Hs seems to suggest

**V**

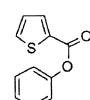
MMX Energy: 19.29 Kcal

**VI**

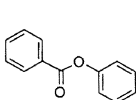
27.62 Kcal

**VII**

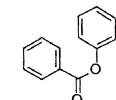
33.19 Kcal

**VIII**

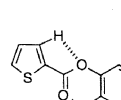
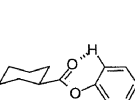
39.97 Kcal

**IX**

31.86 Kcal

**X**

39.14 Kcal

**XI****XII**

the presence of hydrogen bonding. However, a similar kind of line broadening of the thieryl-*o*-H and benzoyl-*o*-H is not observed. Therefore, the interaction between the thieryl-*o*-H (and benzoyl-*o*-H) and phenoxy oxygen atoms may be merely stereoelectronic in nature.

## Experimental Section

Melting points were determined on a Fischer MEL-TEMP apparatus and are uncorrected. PCMODEL calculations were performed on a Macintosh Quadra 610 with molecular modeling software from Serena Software, Bloomington, Indiana. Nuclear magnetic resonance (NMR) spectra were recorded on a Bruker DPX-400 FT NMR spectrometer in the Central Lab of Kangwon National University with chloroform-*d* as the solvent at 400 MHz for  $^1\text{H}$  and 100 MHz for  $^{13}\text{C}$ .  $^1\text{H}$  chemical shift values were referenced to tetramethylsilane, whereas those of  $^{13}\text{C}$ s were referenced to the central peak of  $\text{CDCl}_3$  as 77.00 ppm. The concentration of the solution was 0.10 M. Infrared (ir) spectra were recorded on a JASCO Model IR Report-100 spectrophotometer as potassium bromide pellets or neat. Electron-impact mass spectra (ms) were obtained using a JEOL JMS-AX505WA mass spectrometer in the Research Center for New-Biomaterials in Agriculture, Seoul National University, Suwon. Elemental analyses were performed by the M-II-W Laboratories, Phoenix, Arizona.

**An Illustrative Procedure for the Ester 1 and 2.** A mixture of 2-thiophenecarbonyl chloride (0.4 mL, 40 mmole), pyridine (0.7 mL) and phenol (0.54 g, 60 mL) was heated to reflux for 30 min. The solution was mixed with water (20 mL) and extracted with ethyl acetate ( $3 \times 15$  mL). The extract was washed with saturated  $\text{NaHCO}_3$  solution (10 mL) and then dried with  $\text{MgSO}_4$ . After evaporation of the solvent, white residue resulted, which was recrystallized from ethanol.

**1a.** 60%, mp 98-100 °C; ir (KBr) 3080 w, 1730 s, 1520 s, 1350 s, 1250 s, 1200 vs., 1180 vs., 1040 s, 815 w, 730 w; mass, *m/z* (%) 249 (31,  $\text{M}^+$ ), 219 (4), 113 (58), 112 (76), 111 (100,  $\text{C}_4\text{H}_3\text{S}=\text{O}^+$ ), 95 (64), 83 (61,  $\text{C}_4\text{H}_3\text{S}^+$ ).

Anal. Calcd for  $\text{C}_{11}\text{H}_7\text{NO}_2\text{S}$  (249.24): C, 53.01; H, 2.83; N, 5.62; S, 12.86. Found: C, 53.10; H, 2.65; N, 5.72; S, 12.64.

**1b.** 38%, mp 60-62 °C; ir (KBr) 3030 w, 1720 s, 1565 m, 1240 s, 1210 s, 1195 s, 1035 s, 840 w, 770 m, 735 m; mass, *m/z* (%) 284 (66,  $\text{M}^+ + 2$ ), 282 (64,  $\text{M}^+$ ), 145 (6), 143 (6), 113 (52), 112 (69), 111 (100,  $\text{C}_4\text{H}_3\text{S}-\text{C}=\text{O}^+$ ), 83 (55,  $\text{C}_4\text{H}_3\text{S}^+$ ).

Anal. Calcd for  $\text{C}_{11}\text{H}_7\text{BrO}_2\text{S}$  (283.14): C, 46.66; H, 2.49; Br, 28.22; S, 11.32. Found: C, 46.80; H, 2.36; Br, 28.09; S, 11.16.

**1c.** 52%, mp 47-49 °C; ir (KBr) 3030 w, 1715 s, 1580 s, 1245 s, 1220 s, 1195 s, 1040 s, 875 m, 770 m, 725 m, 700 s; mass, *m/z* (%) 240 (28,  $\text{M}^+ + 2$ ), 238 (77,  $\text{M}^+$ ), 113 (39), 112 (49), 111 (100,  $\text{C}_4\text{H}_3\text{S}-\text{C}=\text{O}^+$ ), 83 (40,  $\text{C}_4\text{H}_3\text{S}^+$ ).

Anal. Calcd for  $\text{C}_{11}\text{H}_7\text{ClO}_2\text{S}$  (238.68): C, 55.35; H, 2.96; Cl, 14.85; S, 13.43. Found: C, 55.18; H, 2.86; Cl, 14.87; S,

13.21.

**1d.** 21%. viscous liquid; ir (neat) 3070 vw, 2950 w, 1720 s, 1120 s, 1040 m, 855 w, 740 m; mass. m/z (%) 234 (62, M<sup>+</sup>), 113 (11), 112 (15), 111 (100, C<sub>4</sub>H<sub>3</sub>S-C≡O<sup>+</sup>), 83 (13, C<sub>4</sub>H<sub>3</sub>S<sup>+</sup>).

Anal. Calcd for C<sub>12</sub>H<sub>10</sub>O<sub>3</sub>S (234.27): C, 61.52; H, 4.30; S, 13.69. Found: C, 61.34; H, 4.60; S, 13.45.

**1e.** 48%. mp 80-81 °C; ir (KRr) 3055 vw, 1705 s, 1235 s, 840 m, 775 w, 740 m, 720 m; mass. m/z (%) 218 (59, M<sup>+</sup>), 149 (13), 112 (14), 111 (100, C<sub>4</sub>H<sub>3</sub>S-C≡O<sup>+</sup>), 83 (12, C<sub>4</sub>H<sub>3</sub>S<sup>+</sup>).

Anal. Calcd for C<sub>12</sub>H<sub>10</sub>O<sub>3</sub>S (218.27): C, 66.03; H, 4.62; S, 14.69. Found: C, 66.28; H, 4.82; S, 14.81.

**1f.** 52%. mp 174-175 °C; ir (KRr) 3070 w, 1715 s, 1520 s, 1345 ms, 1195 vs, 1040 s, 750 s; mass. m/z (%) 249 (33, M<sup>+</sup>), 167 (11), 149 (23), 113 (58), 112 (76), 111 (100, C<sub>4</sub>H<sub>3</sub>S-C≡O<sup>+</sup>), 95 (13), 83 (60, C<sub>4</sub>H<sub>3</sub>S<sup>+</sup>).

Anal. Calcd for C<sub>11</sub>H<sub>7</sub>NO<sub>4</sub>S (249.24): C, 53.01; H, 2.83; N, 5.62; S, 12.86. Found: C, 53.10; H, 2.65; N, 5.72; S, 12.64.

**1g.** 50%. mp 84-85 °C; ir (KRr) 3050 w, 1705 s, 1475 s, 1190 vs, 1040 s, 740 s; mass. m/z (%) 284 (77, M<sup>+</sup> + 2), 282 (72, M<sup>+</sup>), 145 (10), 143 (10), 113 (50), 112 (64), 111 (100, C<sub>4</sub>H<sub>3</sub>S-C≡O<sup>+</sup>), 83 (51, C<sub>4</sub>H<sub>3</sub>S<sup>+</sup>).

Anal. Calcd for C<sub>11</sub>H<sub>7</sub>BrO<sub>2</sub>S (283.14): C, 46.66; H, 2.49; Br, 28.22; S, 11.32. Found: C, 46.44; H, 2.40; Br, 28.39; S, 10.67.

**1h.** 69%. mp 82-83 °C; ir (KRr) 3070 w, 1710 s, 1490 s, 1405 s, 1205 s, 1190 vs, 1045 s, 740 s; mass. m/z (%) 240 (20, M<sup>+</sup> + 2), 238 (55, M<sup>+</sup>), 113 (27), 112 (35), 111 (100, C<sub>4</sub>H<sub>3</sub>S-C≡O<sup>+</sup>), 83 (29, C<sub>4</sub>H<sub>3</sub>S<sup>+</sup>).

Anal. Calcd for C<sub>11</sub>H<sub>7</sub>ClO<sub>2</sub>S (238.68): C, 55.35; H, 2.96; Cl, 14.85; S, 13.43. Found: C, 55.50; H, 2.80; Cl, 15.00; S, 13.40.

**1i.** 60%. mp 104-105 °C; ir (KRr) 3055 w, 2960 w, 1720 s, 1500 s, 1245 s, 1195 s, 1175 vs, 840 m, 725 m; mass. m/z (%) 234 (49, M<sup>+</sup>), 112 (13), 111 (100, C<sub>4</sub>H<sub>3</sub>S-C≡O<sup>+</sup>), 83 (10, C<sub>4</sub>H<sub>3</sub>S<sup>+</sup>).

Anal. Calcd for C<sub>12</sub>H<sub>10</sub>O<sub>3</sub>S (234.27): C, 61.52; H, 4.30; S, 13.69. Found: C, 61.72; H, 4.50; S, 13.49.

**1j.** 60%. mp 85-87 °C; ir (KRr) 3050 w, 2850 w, 1705 vs, 1255 s, 1220 s, 1175 s, 1040 s, 840 m, 740 s; mass. m/z (%) 218 (72, M<sup>+</sup>), 113 (15), 112 (19), 111 (100, C<sub>4</sub>H<sub>3</sub>S-C≡O<sup>+</sup>), 83 (16, C<sub>4</sub>H<sub>3</sub>S<sup>+</sup>).

Anal. Calcd for C<sub>12</sub>H<sub>10</sub>O<sub>3</sub>S (218.27): C, 66.03; H, 4.62; S, 14.69. Found: C, 66.19; H, 4.74; S, 14.50.

**1k.** 53%. mp 44-46 °C; ir (KRr) 3050 w, 1720 vs, 1405 s, 1265 s, 1240 s, 1165 vs, 1040 s, 850 w, 730 s; mass. m/z (%) 204 (15, M<sup>+</sup>), 113 (5), 112 (6), 111 (100, C<sub>4</sub>H<sub>3</sub>S-C≡O<sup>+</sup>), 83 (55, C<sub>4</sub>H<sub>3</sub>S<sup>+</sup>).

Anal. Calcd for C<sub>11</sub>H<sub>9</sub>O<sub>2</sub>S (204.24): C, 64.69; H, 3.95; S, 15.70. Found: C, 64.75; H, 4.10; S, 15.41.

**2a.** 85%. mp 93-94 °C (lit.<sup>18c</sup> 95 °C); ir (KRr) 3060 w, 1730 s, 1530 s, 1350 s, 1195 vs, 1040 s, 810 m; mass. m/z (%) 243 (0.2, M<sup>+</sup>), 139 (1.8), 105 (100, C<sub>6</sub>H<sub>5</sub>-C≡O<sup>+</sup>), 77 (83).

**2b.** 50%. mp 83-85 °C (lit.<sup>18d</sup> 86 °C); ir (KRr) 3050 w, 1710 s, 1140 s, 830 s; mass. m/z (%) 278 (1.5, M<sup>+</sup> + 2), 276 (1.4, M<sup>+</sup>), 145 (6.5), 143 (6.7), 119 (2.6), 117 (2.7), 105

(100, C<sub>6</sub>H<sub>5</sub>-C<sup>+</sup>), 77 (70).

**2c.** 68%. mp 65-68 °C (lit.<sup>18a</sup> 71 °C); ir (KRr) 3060 w, 1720 s, 1595 s, 1190 s, 1055 s, 860 m, 780 m, 710 m; mass. m/z (%) 234 (1.3, M<sup>+</sup> + 2), 232 (3.7, M<sup>+</sup>), 141 (1.0), 139 (3.6), 113 (1.1), 111 (3.2), 105 (100, C<sub>6</sub>H<sub>5</sub>-C≡O<sup>+</sup>), 99 (41), 77 (100).

**2d.** 69%. viscous liquid; ir (neat) 3030 w, 2900 w, 1710 vs, 1600 m, 1260 s, 1110 s, 840 w, 760 m, 700 s; mass. m/z (%) 228 (9.2, M<sup>+</sup>), 123 (1.0), 105 (100, C<sub>6</sub>H<sub>5</sub>-C≡O<sup>+</sup>), 95 (18), 85 (11), 83 (17), 77 (83).

**2e.** 64%. 55 °C (lit.<sup>19</sup> 55-56 °C); ir (KRr) 3010 w, 2930 w, 2870 w, 1720 s, 1250 s, 1230 s, 1120 m, 840 m, 760 m; mass. m/z (%) 212 (7.5, M<sup>+</sup>), 105 (100, C<sub>6</sub>H<sub>5</sub>-C≡O<sup>+</sup>), 77 (100).

**2f.** 70%. mp 143-144 °C (lit.<sup>18f</sup> 142.5 °C); ir (KRr) 3060 w, 1730 s, 1520 s, 1360 m, 1180 m, 1150 s, 840 s; mass. m/z (%) 243 (10, M<sup>+</sup>), 139 (6.7), 106 (58), 105 (100, C<sub>6</sub>H<sub>5</sub>-C≡O<sup>+</sup>), 85 (10), 77 (100).

**2g.** 63%. mp 102-103 °C (lit.<sup>18d</sup> 58.5 °C); ir (KRr) 3050 w, 1720 vs, 1200 s, 1050 s, 870 m, 800 m, 710 ms; mass. m/z (%) 278 (3.3, M<sup>+</sup> + 2), 276 (3.3, M<sup>+</sup>), 173 (5.1), 171 (5.7), 145 (24), 143 (25), 119 (10), 117 (10), 105 (100, C<sub>6</sub>H<sub>5</sub>-C≡O<sup>+</sup>), 77 (100).

**2h.** 62%. mp 86-87 °C (lit.<sup>18b</sup> 88 °C); ir (KRr) 3050 w, 1720 s, 1150 s, 1080 s, 840 s; mass. m/z (%) 234 (0.8, M<sup>+</sup> + 2), 232 (2.4, M<sup>+</sup>), 141 (0.9), 139 (2.7), 129 (91.4), 127 (4.4), 105 (100, C<sub>6</sub>H<sub>5</sub>-C≡O<sup>+</sup>), 77 (100).

**2i.** 84%. mp 84-86 °C (lit.<sup>18b</sup> 87 °C); ir (KRr) 3030 w, 2900 w, 1720 s, 1180 vs, 1050 s, 820 m; mass. m/z (%) 228 (15, M<sup>+</sup>), 123 (23), 106 (16), 105 (100, C<sub>6</sub>H<sub>5</sub>-C≡O<sup>+</sup>), 95 (32), 77 (83).

**2j.** 89%. mp 66-69 °C (lit.<sup>18b</sup> 70 °C); ir (KRr) 3030 w, 2900 w, 1710 vs, 1270 s, 1180 vs, 1050 vs, 800 m; mass. m/z (%) 212 (6.2, M<sup>+</sup>), 105 (100, C<sub>6</sub>H<sub>5</sub>-C≡O<sup>+</sup>), 79 (12), 77 (83).

**2k.** 83%. mp 68-69 °C (lit.<sup>18b,19</sup> 70 °C); mass. m/z (%) 198 (14, M<sup>+</sup>), 105 (100, C<sub>6</sub>H<sub>5</sub>-C≡O<sup>+</sup>), 77 (47).

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