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# Gas-phase Acidity and Liquid Phase $pK_a$ Calculations of Some Cyclic Oxocarbon Acids ( $C_nO_nH_2$ ( $n = 3, 4, 5, 6$ )): A Theoretical Investigation

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## Abstract

The gas-phase acidity and the  $pK_a$  values of the organic acids have been attracting a lot of attention from organic and analytical chemists. The gas-phase acidity and  $pK_a$  calculations for some oxocarbon acids were investigated under B3LYP/6-311+G(d,p) level of theory. In this study, four oxocarbon acids,  $C_nO_nH_2$  were selected, namely deltic acid ( $n = 3$ ), squaric acid ( $n = 4$ ), croconic acid ( $n = 5$ ) and rhodizonic acids ( $n = 6$ ). The calculations in gas phase show that the gas-phase acidity of the acids increases as the ring size increases due to the formation of resonance-stabilized monoanions and dianions. Solvation free energy is required in  $pK_a$  calculation. However, there is significant uncertainty in calculating the solvation free energy using theoretical methods. Therefore, three methods to calculate the free energy of solvation were adopted for comparison, which are the (i) solvent reaction field (SCRF) method using the Simple United Atom Topological Model (UA0); (ii) SCRF using the United Atom Topological Model (UAHF) optimized for HF/6-31G(d) level of theory; and (iii) Langevin dipoles (LD) method. From the results obtained, it was shown that SCRF method with UAHF atomic radii has the potential of reproducing the experimental values. The calculated  $pK_a$  values were in good agreement with experimental results and have shown that the croconic acid,  $C_5O_5H_2$  is found to be the most acidic in aqueous phase.

**Keywords:**  $pK_a$ ; gas phase acidity; oxocarbon acids; solvation energy; LD method; DFT calculation

## 1. Introduction

Cyclic oxocarbon acids,  $C_nO_nH_2$  studied in this work are diprotic organic acids in which upon deprotonation of the two protons, it will form cyclic oxocarbon dianions consisting of only carbon and oxygen atoms. The cyclic oxocarbon dianions,  $C_nO_n^{2-}$  are one of the many groups in the oxocarbon family. The dianions have  $sp^2$  orbitals on all the carbon atoms, allowing the delocalization of the negative charge and thus enhancing their acidities.

The cyclic oxocarbon acid and dianions, ( $n = 3, 4, 5, 6$ ) were synthesized many years ago. The two smallest cyclic oxocarbon acids; deltic acid ( $C_3O_3H_2$ ),<sup>1</sup> squaric acid ( $C_4O_4H_2$ )<sup>2,3</sup> and their respective dianions were synthesized recently but croconic acid ( $C_5O_5H_2$ )<sup>4</sup> and rho-

dizonic acid ( $C_3O_3H_2$ )<sup>5</sup> along with their dianions have been known since more than a century ago.

Many studies have been done to investigate the structure and aromaticity of oxocarbon dianions because they exhibit high degree of electron delocalization which has become the subject for several studies.<sup>6-8</sup> It was found that the aromaticity of oxocarbon dianions decreases as the ring size increases. Many studies on the spectroscopic investigations<sup>9-11</sup> were done to investigate the vibrational spectroscopy of oxocarbon dianions. For instance, a theoretical and experimental study was conducted by Oliveira et al.<sup>12</sup> to investigate the vibrational spectroscopy and aromaticity of different squarate salts and it was reported that the degree of electron delocalization and aromaticity increases with increasing size of the counter-ions. Other than that, the structure and aromaticity of thiocarbon com-

pounds, the analogue of oxocarbons have also been investigated in various theoretical studies using nucleus independent chemical shift, NICS method.<sup>13,14</sup>

The derivatives of oxocarbon acids have been the subject in various theoretical investigations on the acidity of the compounds. Zhou et al.<sup>15–17</sup> have reported on the structure, aromaticity and gas phase acidity of different derivatives and analogues of squaric acid in their studies. One of the derivatives studied, 1,2-dithiosquaric acid was found to be not aromatic as it has no  $\pi$ -electron delocalization. The aromaticity and acidity of derivatives of nitrogen squaric acid was investigated by Xue et al.<sup>18</sup> and it was also found that not all the derivatives of squaric acid exhibit full aromaticity.

The cyclic oxocarbon acids under study and their derivatives were known to have some applications in medicinal and industrial field. The smallest acid, deltic acid has very little application while the other cyclic oxocarbon acids and their derivatives offer a wide range of use in industrial field. Squaric acid is known to be a good catalyst in several reactions such as the Mukaiyama aldol and Michael reactions.<sup>19</sup> It can also be used as a green and environmentally friendly catalyst in Michael and Mannich-type reactions.<sup>20,21</sup> Croconic acid derivatives are being used as dyes in many companies and many of them have acquired patent for the research.<sup>22</sup> Rhodizonic acid on the other hand is used to detect lead as it changes colour from goldenrod to pink when exposed to lead.<sup>23,24</sup> In medical field, squaric acid dibutylester (SADBE) is very well known in the treatment of warts disease.<sup>25–27</sup> It was also reported that rhodizonic acid has blood sugar lowering effect in rabbits.<sup>28</sup>

Many theoretical studies have been conducted to calculate the  $pK_a$  values of the organic acids. However, until now, accurate calculation of  $pK_a$  values using theoretical method has been the main problem as there is no precise way of calculating the free energy of solvation of a proton due to significant uncertainty in the value obtained. Therefore, an experimental value for free energy of solvation was adopted in our calculation and it was recently measured as  $-1104.5 \text{ kJ mol}^{-1}$ , which is equal to  $-264.23 \text{ kcal mol}^{-1}$ .<sup>29</sup> The recent work by Mavri et al. also adopted the same value of free energy solvation of proton in their calculations.<sup>30,31</sup> Due to the ambiguous theoretical methods in calculating  $pK_a$  values for organic acids, numerous methods had been attempted in the past to reproduce experimental results. Most research use the simple polarizable continuum model (PCM) to obtain the solvation free energy.<sup>32–34</sup> In the course of achieving a better accuracy, Pliego et al. proposed a hybrid method by explicitly including the solvent molecules in the organic system and obtaining the solvation energy of the clusters using continuum calculation.<sup>35–37</sup> Another method was proposed by Cerar et al. to predict the  $pK_a$  values of polyprotic acid through the relationship between surface-electrostatic potentials with the known aqueous acidities of the acid.<sup>38</sup> A

research to determine the  $pK_a$  values of acetates in water reported that the use of a mixed QM/MM-Ewald simulations were able to give accurate and consistent evaluation of the values of acetates and bicarbonate ions.<sup>39</sup> The search for alternative methods to calculate the  $pK_a$  values more accurately and consistently is still ongoing and a commentary by Coote and co-workers discussed the potential errors and solutions to this problem.<sup>40</sup>

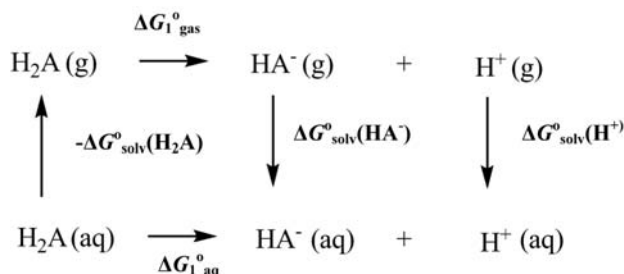
The  $pK_a$  values of the oxocarbon acids were previously determined in experimental works, with the use of pH potentiometry, conductometry and spectrophotometry methods.<sup>41–44</sup> However, to the best of our knowledge, there is no study reported on theoretical investigation of the  $pK_a$  value of acids,  $C_nO_nH_2$ . Therefore, deltic acid ( $n = 3$ ), squaric acid ( $n = 4$ ), croconic acid ( $n = 5$ ) and rhodizonic acid ( $n = 6$ ) were selected in this present work to determine the  $pK_a$  values for the first and second dissociation. Since the calculation of the gas-phase acidity and the  $pK_a$  values depends on the calculation of the solvation free energy, three methods of calculation were used to calculate the solvation free energy, which are LD method by Florian and Warshel, and the two different molecular cavities calculations in Polarizable Continuum Model (SCRF/PCM) implemented in Gaussian03 program. Molecular cavity used in the SCRF calculation also affects the value of solvation free energies obtained. In this study, the two molecular cavities used are the Simple United Atom Topological Atom (UA0) and the United Atom Topological Atom (UAHF) which is optimized for HF/6-31G(d) level of theory. By using the information obtained from the theoretical calculations and in comparison with the experimental studies we hope we can draw a conclusion for a suitable theoretical method to predict gas-phase acidity and the  $pK_a$  values. Besides, this study may help with other types of organic acids in the absence of experimental results.

## 2. Computational Method

Gas-phase acidity and the  $pK_a$  value of the following acids: deltic acid, squaric acid, croconic acid and rhodizonic acid were investigated using the theoretical calculations. All calculations were done with the Gaussian03 program package.<sup>45</sup> The geometries of the neutral, anion and dianion structures in the gas phase of each acid were optimized under B3LYP/6-311+G(d,p) density functional theory levels. The applied DFT method B3LYP utilizes the Becke three parameter hybrid gradient-corrected exchange functional,<sup>46</sup> combined with the gradient-corrected correlation functional of Lee, Yang and Parr.<sup>47</sup> Vibrational analysis was performed on the optimized structures and there is no imaginary frequency found for all the structures, indicating that all of them are in their ground state energy level. The energies of the structures were corrected for the zero point vibrational energy. Gas-phase acidity of

Brönsted acids is defined as the free energy of deprotonation.<sup>48</sup> Using the thermodynamic parameters obtained from the results of calculations, the gas-phase acidity of each acid under study can be predicted.

The free energies of solvation of the structures under study were obtained using the solvent model chemistry of Barone et al.<sup>49</sup> in Gaussian03 through two different molecular cavities calculations and the Langevin dipoles model (LD) by Florian and Warshel.<sup>50–52</sup> Using the optimized geometries in gas phase obtained from B3LYP/6-311+G(d,p) as the input, we utilized the Polarizable Continuum Model (SCRF/PCM) calculation with SCFVAC keyword implemented in Gaussian03 program to perform a full optimization in water solvent with two different molecular cavities, UA0 and UAHF. While for the UA0 atomic radii calculation, B3LYP/6-311+G(d,p) was used in gas phase calculations, for UAHF atomic radii, HF/6-31G(d) was utilized. The optimized structures in aqueous phase show no imaginary frequency, indicating that all of them are in their ground state energy level. Merz-Kollman atomic charges of the optimized geometries in gas phase obtained from B3LYP/6-311+G(d,p) level of theory were used as the input for LD model. The free energies of solvation were used to calculate the aqueous free energy of reaction by using the thermodynamic shown in Scheme 1. The similar cycle was used in a study by Kennedy et al.<sup>33</sup>



**Scheme 1:** Thermodynamic cycle

The following equations (1) to (6) are used to calculate the aqueous free energy of reaction and the  $pK_a$  value. A correction of  $-RT \ln V$  is also required in the calculations, to convert from a standard state of 1 atm to 1 M.

$$\Delta G_{I, \text{ solv}}^{\circ} = \Delta G_{\text{ solv}}^{\circ}(\text{HA}^-) + \Delta G_{\text{ solv}}^{\circ}(\text{H}^+) - \Delta G_{\text{ solv}}^{\circ}(\text{H}_2\text{A}) \quad (1)$$

$$\Delta G_{I, \text{ aq}}^{\circ} = \Delta E_{I, \text{ gas}}^{\circ} + \Delta G_{I, \text{ solv}}^{\circ} \quad (2)$$

$$pK_{a1} = \Delta G_{I, \text{ aq}}^{\circ} / (2.303RT) \quad (3)$$

$$\Delta G_{2, \text{ solv}}^{\circ} = \Delta G_{\text{ solv}}^{\circ}(\text{A}^{2-}) + \Delta G_{\text{ solv}}^{\circ}(\text{H}^+) - \Delta G_{\text{ solv}}^{\circ}(\text{HA}^-) \quad (4)$$

$$\Delta G_{2, \text{ aq}}^{\circ} = \Delta E_{2, \text{ gas}}^{\circ} + \Delta G_{2, \text{ solv}}^{\circ} \quad (5)$$

$$pK_{a2} = \Delta G_{2, \text{ aq}}^{\circ} / (2.303RT) \quad (6)$$

where,  $R = 1.986 \text{ cal mol}^{-1} \text{ K}^{-1}$  and  $T = 298 \text{ K}$ .

### 3. Results and Discussions

#### 3. 1. Structural Analysis

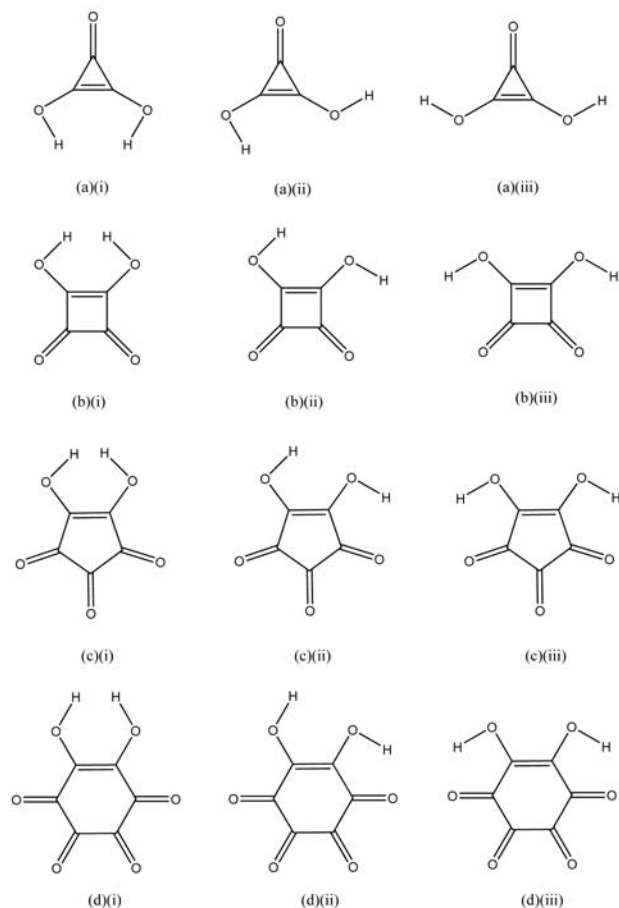
The acids under study can exist in three conformations depending on the position of one O-H bond relative to the other O-H bond. Figure 1 shows the structures of the three conformations of each acid. The structures were fully optimized under B3LYP/6-311+G(d,p) in gas phase and the energies were reported as shown in Table 1. The energies were corrected with their corresponding zero point vibrational energies. It can be seen from Table 1 that the ZZ isomer is the most stable among the three isomers for all the acids under study, followed by ZE isomer and lastly EE isomer. This finding is consistent with the results found in previous studies by Zhou et al.<sup>15–17</sup> in which the investigations on different derivatives of squaric acid were done. Since the ZZ isomer is the most stable among the three isomers, only the information of ZZ isomer is used in the calculation of gas-phase acidity. Other than that, only the structure of the ZZ isomer of each acid was used as input for optimization in aqueous phase. The point group of all the optimized EE isomers is  $C_{2v}$  except for the slightly twisted isomer of croconic and rhodizonic acid in which their point group is  $C_2$ . All the ZE isomers have  $C_s$  point group except for the ZE isomer of rhodizonic acid which is in a twisted conformation, has  $C_1$  point group. Lastly, the ZZ isomers of the acids have  $C_{2v}$  point group except for ZZ isomer of croconic acid having  $C_s$  point group and ZZ isomer of rhodizonic acid having  $C_2$  point group.

**Table 1:** The total energies,  $E_T$  of the three isomers of each acid corrected with zero point vibrational energy, ZPVE, as calculated with B3LYP/6-311+G(d,p).

Compounds	Total Energy, $E_T$ / a.u. <sup>b</sup>		
	EE	ZE	ZZ
Deltic acid	-341.149212 (0.048198) <sup>a</sup>	-341.154621 (0.048572)	-341.156678 (0.048729)
Squaric acid	-454.534317 (0.058495)	-454.543751 (0.059365)	-454.547146 (0.059605)
Croconic acid	-567.894264 (0.068612)	-567.909828 (0.069645)	-567.915118 (0.070021)
Rhodizonic acid	-681.222878 (0.077837)	-681.243079 (0.079152)	-681.248664 (0.079501)

<sup>a</sup> The values in parentheses are the zero point vibrational energies, ZPVE.

<sup>b</sup> The values of the total energies have been corrected with zero point vibrational energy,  $E_T = E_{\text{species}} + \text{ZPVE}$ .



**Figure 1:** The structures of the different conformations of each acid. (a) i) E,E-deltic acid, (a)ii) Z,E-deltic acid, (a)iii) Z,Z-deltic acid; (b) i) E,E-squaric acid, (b)ii) Z,E-squaric acid, (b)iii) Z,Z-squaric acid; (c) i) E,E-croconic acid, (c)ii) Z,E-croconic acid, (c)iii) Z,Z-croconic acid; (d) i) E,E-rhodizonic acid, (d)ii) Z,E-rhodizonic acid, (d)iii) Z,Z-rhodizonic acid.

### 3. 2. Gas-phase Acidity

The acids' acidity is investigated because they yield resonance-stabilized anions after dissociation and have been the subject of many investigations. Some of the acids under study even produce aromatic dianions after dissociation. It was found that the aromaticity of dianion decreases as the ring size increases.<sup>5</sup> Regardless, the formation of these resonance-stabilized dianions was predicted to be the main factor that pushes the equilibrium to the right, favouring the dissociation of the protons. The structures of dianions  $C_nO_n^{2-}$  ( $n = 3-5$ ) favour the  $D_{nh}$  symmetry except for rhodizonate ion,  $C_6O_6^{2-}$  where its  $D_{6h}$  symmetry was found to have 3 imaginary frequencies. However, its energy minimum has a  $D_{3d}$  symmetry with no imaginary frequency.

Gas-phase acidity is defined as the free energy of deprotonation.<sup>41</sup> The gas-phase acidity of each acid is investigated under B3LYP/6-311+G(d,p) level of theory be-

cause a study has shown that this method and basis set is the most suitable for squaric acid.<sup>17</sup> Hence, we use the same level of theory for the other acids. Table 2 and 3 show the energy contribution to the first and second dissociation of the acids, respectively.

**Table 2:** Energy contribution to the free energy of first dissociation  $H_2A(g) \rightarrow HA^-(g) + H^+(g)$  (in kcal mol<sup>-1</sup>)

Compounds	$\Delta E_1$	$\Delta(ZPVE)_1$	$\Delta H_1$	$-T\Delta S_1$	$\Delta G_1^\circ$
Deltic acid	323.82	-8.45	323.72	-0.31	323.41
Squaric acid	311.29	-8.00	311.09	-0.09	311.00
Croconic acid	305.54	-8.00	305.35	0.21	305.56
Rhodizonic acid	303.18	-8.00	302.98	-0.09	302.89

**Table 3:** Energy contribution to the free energy of second dissociation  $HA^-(g) \rightarrow A^{2-}(g) + H^+(g)$  (in kcal mol<sup>-1</sup>)

Compounds	$\Delta E_2$	$\Delta(ZPVE)_2$	$\Delta H_2$	$-T\Delta S_2$	$\Delta G_2^\circ$
Deltic acid	438.50	-7.53	438.06	1.87	439.93
Squaric acid	419.55	-7.76	419.22	1.80	421.02
Croconic acid	409.66	-8.06	409.46	1.54	411.00
Rhodizonic acid	403.84	-8.10	403.72	0.45	404.17

From the tables, it is shown that the free energy of dissociation decreases as the ring size increases. This indicates that the gas-phase acidity increases as the ring size increases. Therefore, the acidity of rhodizonic acid is the highest followed by croconic acid, squaric acid and lastly deltic acid. This phenomenon is due to the negative charge of the anions being delocalized into a bigger ring and produces more resonance forms. Hence, the stability of the negatively charged species increases as the ring size increases. Other than that, it was found that the free energies of the second dissociation of the acids are higher than the free energies of the first dissociation, indicating that the second dissociation is less preferable compared to the first dissociation. The dissociation of the second proton involves the extraction of proton from a negatively charged species (the anion formed from the first dissociation) in which is more difficult compared to the dissociation of proton from a neutral species because the proton is more tightly bound to the anion. As a summary, rhodizonic acid ( $n = 6$ ) shows the highest acidity in both the first and second dissociation. Therefore, it can be concluded that it has the highest gas-phase acidity among the acids studied in this work.

### 3. 3. pK<sub>a</sub> Calculation

The calculation of pK<sub>a</sub> is done by optimizing the structures in aqueous phase and obtaining the thermodynamic parameters. The calculated free energies of dissociation in gas phase, free energies of solvation using SCRF (UA0 and UAHF) and LD methods, aqueous free

**Table 4:** The free energies contribution to the  $pK_a$  calculation of the first dissociation using SCRF and LD methods,  $H_2A(aq) \rightarrow HA^-(aq) + H^+(aq)$  (in kcal mol<sup>-1</sup>)

Compounds	$\Delta E_{1\text{ gas}}^o$	$\Delta G_{1\text{ solv}}^o$ <sup>a</sup>			$\Delta G_{1\text{ aq}}^o$ <sup>b</sup>			$pK_{a1}$			Exp. $pK_{a1}$ Values
		SCRF			SCRF			SCRF			
		UA0	UAHF	LD	UA0	UAHF	LD	UA0	UAHF	LD	
Deltic acid	323.82	-310.27	-316.33	-325.63	13.55	7.49	-1.81	9.94	5.50	-1.33	2.57
Squaric acid	311.29	-304.41	-309.94	-320.87	6.88	1.35	-9.58	5.05	0.99	-7.03	0.54
Croconic acid	305.54	-300.79	-306.12	-318.29	4.75	-0.58	-12.75	3.49	-0.46	-9.35	0.80
Rhodizonic acid	303.18	-299.57	-303.66	-316.34	3.61	-0.48	-13.16	2.65	-0.35	-9.66	4.38

<sup>a</sup> Free energy of solvation provided by the Langevin dipoles (LD) method and solvent reaction field (SCRF) method.  $\Delta G_{1\text{ solv}}^o = \Delta G_{\text{solv}}^o(HA^-) + \Delta G_{\text{solv}}^o(H^+) - \Delta G_{\text{solv}}^o(H_2A)$ . The experimental value for  $\Delta G_{\text{solv}}^o(H^+)$ , -264.23 kcal mol<sup>-1</sup> was adopted in the calculations.

<sup>b</sup>  $\Delta G_{1\text{ aq}}^o = \Delta E_{1\text{ gas}}^o + \Delta G_{1\text{ solv}}^o$

**Table 5:** The free energies contribution to the  $pK_a$  calculation of the second dissociation of the acids using SCRF and LD methods,  $HA^-(aq) \rightarrow A^{2-}(aq) + H^+(aq)$  (in kcal mol<sup>-1</sup>)

Compounds	$\Delta E_{2\text{ gas}}^o$	$\Delta G_{2\text{ solv}}^o$ <sup>a</sup>			$\Delta G_{2\text{ aq}}^o$ <sup>b</sup>			$pK_{a2}$			Exp. $pK_{a2}$ Values
		SCRF			SCRF			SCRF			
		UA0	UAHF	LD	UA0	UAHF	LD	UA0	UAHF	LD	
Deltic acid	438.50	-410.07	-423.06	-435.39	28.43	15.44	3.11	20.86	11.33	2.28	6.03
Squaric acid	419.55	-399.99	-411.17	-425.47	19.56	8.38	-5.92	14.35	6.15	-4.34	3.48
Croconic acid	409.66	-392.71	-403.93	-418.79	16.95	5.73	-9.13	12.44	4.20	-6.70	2.24
Rhodizonic acid	403.84	-389.23	-394.99	-411.51	14.61	8.85	-7.67	10.72	6.49	-5.63	4.65

<sup>a</sup> Free energy of solvation provided by the Langevin dipoles (LD) method and solvent reaction field (SCRF) method.  $\Delta G_{2\text{ solv}}^o = \Delta G_{\text{solv}}^o(A^{2-}) + \Delta G_{\text{solv}}^o(H^+) - \Delta G_{\text{solv}}^o(HA^-)$ . The experimental value for  $\Delta G_{\text{solv}}^o(H^+)$ , -264.23 kcal mol<sup>-1</sup> was adopted in the calculations.

<sup>b</sup>  $\Delta G_{2\text{ aq}}^o = \Delta E_{2\text{ gas}}^o + \Delta G_{2\text{ solv}}^o$

energies of dissociation and the  $pK_a$  values are shown in Table 4 and 5. The values calculated using LD methods are mostly negative while the values calculated using SCRF method are mostly positive. Calculation of  $pK_a$  value is a very delicate matter and is very much affected by the free energies of solvation of each species involved in the reaction. Therefore, the experimental values for the acids were used as reference to determine which method is more favoured in the calculation of solvation free energy of the acids under study.

For the calculation of  $pK_a$  values of the first and second dissociation (Table 4 and Table 5), all of the calculations show that deltic acid has the highest  $pK_a$  value among the acids under study, indicating that deltic acid is the least acidic. However, the order of acidity for the other acids shown in the three calculations differs from one and another. To evaluate which acid is more acidic, we compare the  $pK_a$  values of the first and second dissociation as a whole instead of evaluating the values separately in their respective dissociation reaction. In this light, we conclude that squaric acid is the second least acidic in this study as calculated by the three calculation methods because it has relatively high  $pK_a$  value in both the first and second dissociation. The calculated  $pK_a$  values for the first and second dissociation using UA0 method shows that rhodizonic acid is the most acidic while for UAHF method, it shows that

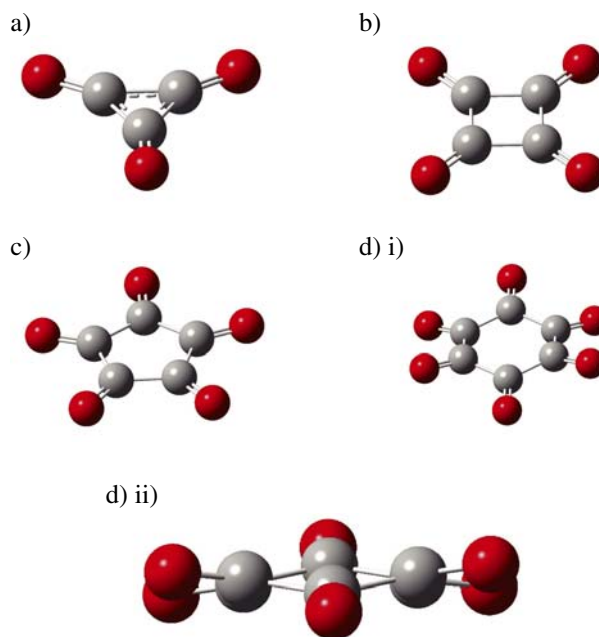
croconic acid is the most acidic. On the other hand, the  $pK_a$  values obtained from LD method are not consistent, showing rhodizonic acid as the most acidic in the first proton dissociation but croconic acid as the strongest in the second dissociation. A general conclusion cannot be made by referring to only the results obtained from these calculations. Therefore, in this case, we look into which method is a more accurate method in calculating the  $pK_a$  values by taking the experimental values as references.

The methods were evaluated in terms of the accuracy in the calculation of solvation free energies by comparing the theoretical and the experimental values. The calculation of  $pK_a$  value is very dependent on the solvation free energies. Until now, there has not been a method known to calculate solvation free energies accurately in theoretical study. From the results obtained, it was found that SCRF method using UA0 atomic radii and LD method produce values at two extreme ends from the experimental values which have significantly large differences. While both of these methods fail to reproduce values close to that of the experimental results, SCRF method using UAHF atomic radii managed to fulfil this task. The values obtained from UAHF method are very much closer to the experimental values compared to UA0 and LD methods. Therefore, it is predicted in this study that UAHF method is a better method in calculating the solvation free energy

which greatly affects the calculation of  $pK_a$  value. This result is consistent to the comment made by Coote et al.<sup>40</sup> whereby it was stated that the more accurate way to calculate the solvation free energy is to use the appropriate level of theory and atomic radii in which the continuum solvent models have been parameterized for optimal performance, and then combine with the gas phase thermodynamic functions calculated at higher level of theory.

After identifying the more accurate method, we can conclude which acid is stronger from here. Since UAHF method is the better method and it shows that croconic acid is the strongest acid, hence the order of acidity calculated by theoretical approach is as follows; deltic < squaric < rhodizonic < croconic. It was mentioned that the gas-phase acidity increases as the ring size increases. Naturally, one would predict that the acidity in aqueous phase follows the same pattern and thus, rhodizonic acid would be predicted to have the lowest  $pK_{a1}$  value. However, croconic acid was identified as the strongest acid in this study based on the results obtained in this study. To explain the enhanced acidity of croconic acid in aqueous phase, we look to the structure of the dianions formed from the proton dissociation. Croconate ion has a planar conformation which allows better overlapping between the p-orbitals in the ring while rhodizonate ion has a slightly twisted conformation which disrupt the perfect overlapping of orbitals. This overlapping of orbitals stabilizes the dianion and pushes the equilibrium to its formation. Thus, this favours the dissociation of protons from the acid. The structures of the dianions are shown in Figure 2.

In summary, the overall acidity of the acid in aqueous phase increases in this order; deltic < squaric < rhodizonic < croconic. The first prediction in this study was that the formation of resonance-stabilized dianion will drive the equilibrium to the product and hence increasing the acidity. One would predict that the higher the aromaticity of the dianion, the higher the acidity. However, this hypothesis was proven incorrect from the theoretical results in this study. In fact, deltic acid which has the highest aromaticity among the compounds studied has shown the lowest acidity among them. A plausible explanation for this is that there are other factors affecting the acidity of the compounds. The experimental works on squaric<sup>53</sup> and croconic acids<sup>43</sup> have shown no relationship between the acidity of the acids with the degree of aromaticity of the compounds. In fact, it was shown that the high degree of acidity is accountable for the more positive value of entropy contributions to the Gibbs free energy of dissociation rather than the energy contributions which are resulted from the stabilization by electron delocalization after dissociation. This was explained in the degree of structuring of water molecules surrounding the acid which affects the entropy of the system. In theoretical study, only the solvent's environment was set up in the calculations without the actual solvent molecules taking part in it, hence causing the theoretical method lacking in this aspect.



**Figure 2:** The structures of the dianions in aqueous phase. a) Deltate ion; b) Squarate ion; c) Croconate ion; d) i) Rhodizonate ion; d) ii) Rhodizonate ion (in a different angle of view to see the slightly twisted conformation)

## 4. Conclusion

The gas-phase acidity and  $pK_a$  calculations for acids,  $C_nO_nH_2$  (where  $n = 3, 4, 5, 6$ ) were investigated under B3LYP/6-311+G(d,p) level of theory. It was found that the gas-phase acidity of the acids increases as the ring size increases due to the formation of resonance-stabilized anions. Rhodizonic acid,  $C_6O_6H_2$  has the highest gas-phase acidity; having free energy of first dissociation,  $\Delta G_1^\circ = 302.89 \text{ kcal mol}^{-1}$  and free energy of second dissociation,  $\Delta G_2^\circ = 404.17 \text{ kcal mol}^{-1}$ . Calculations for  $pK_a$  values were done by optimizing the structures in aqueous phase and using their thermodynamic parameters in the calculations. Three methods of calculation were used to calculate the free energy of solvation of each species involved, which are the, (i) solvent reaction field (SCRF) method using Simple United Atom Topological Model (UA0) and (ii) the United Atom Topological Model (UAHF) optimized for HF/6-31G(d) level of theory; and (iii) Langevin dipoles (LD) method. From the  $pK_a$  values calculated, it was shown that SCRF method with UAHF atomic radii has the potential to reproduce the experimental values and thus, it is a more accurate method to calculate the solvation free energy. From the evaluation of the accuracy of each method and the calculation by theoretical approach, croconic acid,  $C_5O_5H_2$  is found to be the most acidic in aqueous phase in which it has the value of  $pK_{a1} = 3.49$  (UA0),  $-0.46$  (UAHF),  $-9.35$  (LD);  $pK_{a2} = 12.44$  (UA0),  $4.20$  (UAHF),  $-6.70$  (LD).

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## Povzetek

Na B3LYP/6-311+G(d,p) nivoju teorije smo za štiri oksokarbonske kisline,  $C_nO_nH_2$ : 2,3-dihidroksicikloprop-en-1-on ( $n = 3$ ), 3,4-dihidroksiciklobut-3-en-1,2-dion ( $n = 4$ ), 4,5-dihidroksiciklopent-4-en-1,2,3-trion ( $n = 5$ ) in 5,6-dihidroksicikloheks-5-en-1,2,3,4-tetron ( $n = 6$ ) izračunali kislost v plinski fazi in  $pK_a$  vrednosti. Rezultati kažejo, da zaradi tvorbe resonančno stabiliziranih mono- in dianionov kislost v plinski fazi narašča z velikostjo obroča. Za izračun  $pK_a$  vrednosti je potrebno poznavanje solvatacijske energije, za oceno katere smo uporabili tri metode: (i) metodo z vključenim reakcijskim poljem topila («solvent reaction field», SCRf), ki uporablja topološki model združenih atomov (simple united atom topological model, UA0); (ii) SCRf z uporabo UA0 in optimizirano za HF/6-31G(d) nivo teorije (UAHF); ter (iii) metodo Langevinovih dipolov. Izkazalo se je, da od vseh navedenih metoda (ii) z uporabo UAHF atomskih radijev najboljše ponazori dejanske vrednosti. Tudi izračunane  $pK_a$  vrednosti se dobro ujemajo z eksperimentalnimi podatki in kažejo, da ima oksokarbonska kislina s petimi C atomi,  $C_5O_5H_2$ , v vodi najbolj kisel značaj.