

SHORT COMMUNICATION

STABILITY AND REACTIVITY OF THE α -CYCLODEXTRIN COMPLEXES OF 4-METHYLPERBENZOIC ACID

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A kinetic study of the α -cyclodextrin-mediated oxidation of methyl 4-nitrophenyl sulphide by 4-methylperbenzoic acid suggests that the stability constant for the cyclodextrin–peracid complex is two orders of magnitude greater than the value determined previously. Potentiometric studies confirmed this and showed that the 4-methylperbenzoate anion forms a complex of stability similar to that of the molecular acid. A less stable 2:1 cyclodextrin–4-methylperbenzoic acid complex is also observed.

We have extended our previous studies of the stability and reactivity of complexes of cyclodextrin and substituted perbenzoic acids^{1,2} to include the stability of complexes of α -cyclodextrin and substituted methyl phenyl sulphides, sulphoxides and sulphones.³ In this communication we report the effect of α -cyclodextrin on the kinetics of oxygen transfer from 4-methylperbenzoic acid to methyl 4-nitrophenyl sulphide.⁴ The stability constant of the cyclodextrin–peracid complex obtained from the kinetics is inconsistent with that obtained previously using a pH potentiometric method to determine the effect of the cyclodextrin on the pK_a of the peracid.¹ The potentiometric method has been widely used to measure stability constants for a range of weak acids and bases.^{1,5–7} The main limitation of the method, however, is that complex formation involving the molecular acid or its conjugate anion is measured as, respectively, a decrease or an increase in the concentration of hydrogen ion. Hence, in the most extreme case, if the molecular acid and the anion bind equally well, albeit strongly, then no hydrogen ion is released or taken up. This is the same result as when neither species binds. We have repeated our original pK_a measurements and have found that a small systematic error in the original determination of ΔpK_a values led to a serious problem of the type described above.

Figure 1 shows the previously reported¹ effect of α -cyclodextrin on the change of pK_a of substituted perben-

zoic acids in 0.1 mol dm⁻³ sodium nitrate at 25 °C, together with the redetermined data for 4-methylperbenzoic acid. The data are treated using the equation

$$\Delta pK_a = \log \left(\frac{1 + K_{11a}[C] + K_{11a}K_{12a}[C]^2}{1 + K_{11b}[C] + K_{11b}K_{12b}[C]^2} \right) \quad (1)$$

where K_{11a} and K_{11b} are the stability constants for the 1:1 complexes of cyclodextrin with conjugate acid and

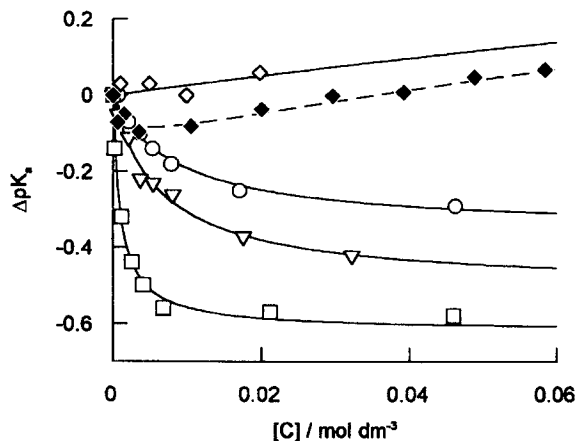


Figure 1. Effect of α -cyclodextrin on the pK_a of perbenzoic acids: diamonds, 4-Me; circles, 4-NO₂; triangles, 4-SO₃⁻; squares, 3-Cl. Open and filled symbols show previously reported¹ and redetermined data, respectively

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conjugate base, respectively, and K_{12a} and K_{12b} are the stability constants of the 2:1 complexes with respect to the 1:1 complexes and cyclodextrin; the total cyclodextrin concentration minus that complexed to the peroxide species is denoted $[C]$.

The curve through the previously reported 4-methylperbenzoic acid points corresponded to a best fit value of $K_{11a} = 6.4 \pm 2.4 \text{ dm}^3 \text{ mol}^{-1}$ with K_{11b} , K_{12a} and K_{12b} set to zero.¹ The redetermined data give K_{11a} , K_{11b} and K_{12a} as 657 ± 354 , 876 ± 443 and $9.6 \pm 1.39 \text{ dm}^3 \text{ mol}^{-1}$, respectively, with K_{12b} set to zero.

Figure 2 shows the effect of cyclodextrin on the second-order rate constant, k_{obs} , for the reaction between 4-methylperbenzoic acid and methyl 4-nitrophenyl sulphide at 25 °C in acetate-acetic acid buffer of pH 4.6 and ionic strength 0.05 mol dm^{-3} . Under these conditions, the sulphide forms both 1:1 and 2:1 cyclodextrin-substrate complexes, with K_{s11} and K_{s12} equal to 123 ± 7 and $152 \pm 17 \text{ dm}^3 \text{ mol}^{-1}$, respectively.³ First-order rate constants were determined using an Applied Photophysics SX-17MV stopped-flow spectrophotometer by following the monoexponential absorbance change at 350 nm during the reaction of $1.6 \times 10^{-5} \text{ mol dm}^{-3}$ methyl 4-nitrophenyl sulphide with a greater than 30-fold excess of peracid. The second-order rate constant, k_{obs} , was the ratio of the first-order rate constant and the peracid concentration. The kinetic data are treated similarly to those for the cyclodextrin-catalysed reaction of iodide and peracids,² with the dependence of k_{obs} on cyclodextrin concentra-

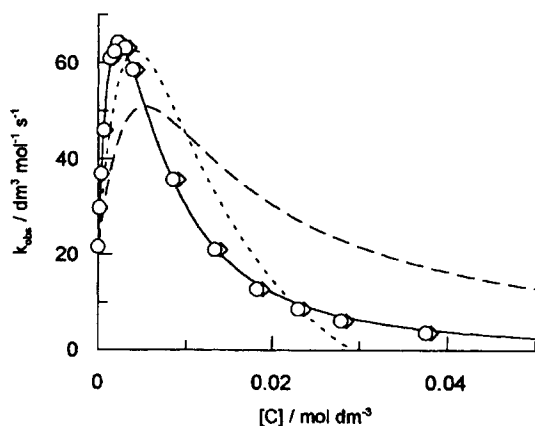


Figure 2. Effect of α -cyclodextrin on the observed second-order rate constant for the reaction of methyl 4-nitrophenyl sulphide and 4-methylperbenzoic acid. Circles and diamonds are computed values of $[C]$ when K_{11a} is set at 592 and $5.8 \text{ dm}^3 \text{ mol}^{-1}$, respectively. The dotted line is the fit to equation (2) when K_{11a} is held constant at $5.8 \text{ dm}^3 \text{ mol}^{-1}$. The dashed line shows the corresponding fit when $k_{2\text{obs}}$ is set to zero. The solid line shows the fit when K_{11a} is included as a parameter in equation (2), yielding a value of $592 \pm 30 \text{ dm}^3 \text{ mol}^{-1}$.

tion being analysed according to the equation

$$k_{\text{obs}} = \frac{k_0 + k_{1\text{obs}}[C] + k_{2\text{obs}}[C]^2}{(1 + K_{s11}[C] + K_{s11}K_{s12}[C]^2)(1 + K_{11a}[C])} \quad (2)$$

using a commercial nonlinear least-squares package, where $k_{1\text{obs}}$ and $k_{2\text{obs}}$ are the observed third- and fourth-order rate constants (first and second order in cyclodextrin, respectively).

The dashed and dotted lines are fits to equation (2) in which K_{11a} is held constant at $5.8 \text{ dm}^3 \text{ mol}^{-1}$, a value that is corrected for the different competitive binding by the nitrate and acetic acid buffer.² (A value of $10 \text{ dm}^3 \text{ mol}^{-1}$ for K_{11a} has been determined for acetic acid using potentiometric and competitive spectrophotometric methods.⁸ The dashed line shows the fit when $k_{2\text{obs}}$ is set to zero. Clearly neither fit describes the data adequately. If, however, K_{11a} is included as a parameter in the equation, then an excellent fit is achieved in which values of $592 \pm 30 \text{ dm}^3 \text{ mol}^{-1}$ and $(77 \pm 2) \times 10^3 \text{ dm}^6 \text{ mol}^{-2} \text{ s}^{-1}$ are obtained for K_{11a} and $k_{1\text{obs}}$, respectively. When a term for K_{12a} is added to equation (2) there is virtually no difference in the best-fit values. The K_{11a} calculated using the kinetic method is in good agreement with that obtained from the potentiometric method and the error is considerably reduced. This kinetically determined value is corrected to $692 \text{ dm}^3 \text{ mol}^{-1}$ to allow for the different competitive binding by the acetic acid buffer and nitrate. The corrected value is substituted into equation (1) and best-fit values of K_{11b} and K_{12a} of $932 \pm 25 \text{ dm}^3 \text{ mol}^{-1}$ and $10.4 \pm 0.9 \text{ dm}^3 \text{ mol}^{-1}$, respectively, are obtained from the potentiometric data when K_{12b} is set to zero. The best fit to the potentiometric data is shown in Figure 3.

The recently published data² for the α -cyclodextrin catalysed reaction between 4-methylperbenzoic acid and

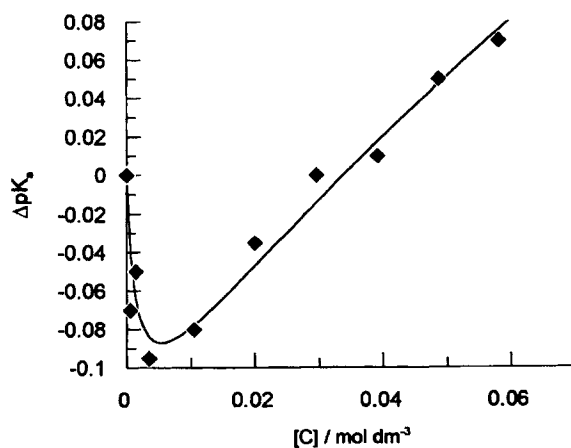


Figure 3. Effect of α -cyclodextrin on the pK_a of 4-methylperbenzoic acid redrawn from Figure 1

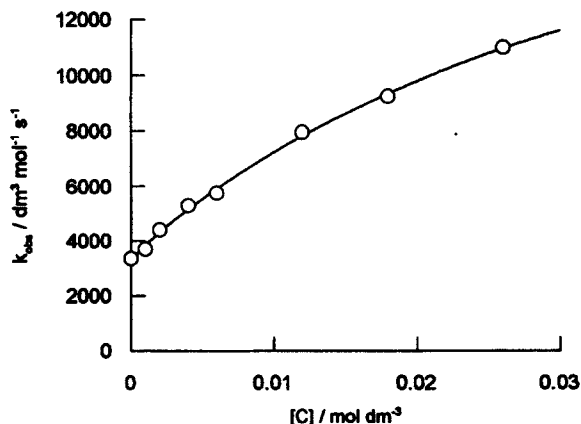


Figure 4. Effect of α -cyclodextrin on the observed second-order rate constant for the reaction of iodide and 4-methylperbenzoic acid

iodide² in acetate-acetic acid buffer of pH 4.8 and ionic strength 0.1 mol dm^{-3} at 25°C are consistent with the value of K_{11a} determined here. This value, corrected for competitive buffer binding, is substituted into equation (3) and the respective best-fit values of $k_{1\text{obs}}$ and $k_{2\text{obs}}$ of $(2.08 \pm 0.09) \times 10^6 \text{ dm}^6 \text{ mol}^{-2} \text{ s}^{-1}$ and $(2.05 \pm 0.05) \times 10^8 \text{ dm}^9 \text{ mol}^{-3} \text{ s}^{-1}$ are obtained. The fit is shown in Figure 4. When a term for K_{12a} is added to the equation

$$k_{\text{obs}} = \frac{k_0 + k_{1\text{obs}}[C] + k_{2\text{obs}}[C]^2}{(1 + K_{11a}[C])(1 + K_1[C])} \quad (3)$$

there is virtually no difference in the best-fit values.

The implications of the present work in terms of our recent studies of the stability and reactivity of cyclodextrin complexes of peracids^{1,2} are extensive and will be discussed in full when we report the kinetics of the cyclodextrin-mediated reactions of peracids and substituted methyl phenyl sulphides. The present results emphasize our assertion² that good independent determinations of stability constants are required not only for the proper interpretation of kinetic parameters but also to ensure their correct determination.

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