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Degradation kinetics of butylmethoxydibenzoylmethane (avobenzone) in aqueous solution

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The degradation kinetics of avobenzone in aqueous solution was studied at 60 ± 0.2 °C over a pH range of 2.0–10.0. The degradation rates were determined by high performance liquid chromatography. The reaction is found to follow first-order kinetics and the rate constant for the decomposition at 25 °C is estimated by extrapolation. The breakdown of avobenzone is shown to be hydroxide ion catalyzed and the Arrhenius plots showed the temperature dependence of avobenzone degradation.

1. Introduction

Avobenzone (parsol 1789), 1-[4-(1,1-dimethylethyl)phenyl]-3-(4-methoxyphenyl)-1,3-propanedione, is a potent UVA sun blocker (Gange 1987; Budavari 2001). Clinically, it is used to prevent deleterious effects of ultraviolet radiations when cosmetic products (example balms, creams and lotions) containing avobenzone are topically applied to the skin. It acts by attenuating more than 90% of UVA radiation (Benda and Steinberg 2000; Herzog et al. 2002). Due to the dependence of efficacy of cosmetic or pharmaceutical preparations on the stability of active substances in the preparations, this study was carried out to investigate the stability of avobenzone in aqueous solutions. Previous studies (Delandre and Lang 1988; Sayre and Dowdry 1999; Warwick and Morison 2004) have reported on the photostabilty of avobenzone. However, there has been no report on the hydrolysis of avobenzone in aqueous solution, and in this paper, we investigated the effects of pH, buffer concentrations, ionic strength and temperature on the stability of avobenzone by high performance liquid chromatographic method.

2. Investigations, results and discussion

The kinetics of decomposition of avobenzone was studied at 60 ± 0.2 °C over the pH range of 2.0–10.0. At pH 2–5, no degradation of avobenzone was observed, but at pH values 7.4–10.0, where degradation occurred, the degradation was found to be of first-order rate kinetics. The decomposition was followed until less than 15% of avobenzone peak height remained. The observed rate constant for the overall degradation of avobenzone was calculated from the slopes of the straight lines obtained by plotting the logarithm of percent remaining versus time under the experimental conditions (Fig. 1). The calculated first-order rate constants at known buffer ionic strength ($\mu = 0.4$) and temperature (60 ± 0.2 °C) are given in Table 1. The pH-rate profile for the decomposition of avobenzone is shown in Fig. 2. As the graph indicates hydroxide ion catalyzed degradation, the overall reaction can be described by the following equation:

$$k_{Obs} = k_O + k_{OH}[OH^-] \qquad (1)$$

where k_{Obs} is the observed apparent first-order rate constant, k_{OH} is the apparent hydroxide ion catalytic rate constant and k_O is the apparent catalytic rate constant of spontaneous or water catalyzed degradation. The apparent first-order rate constant for the water-catalyzed and the second-order rate constant for hydroxide ion catalyzed degradation were determined to be 0.1607/h and 2210/mol/h respectively. The catalytic effect of buffer species used in the kinetic investigation was determined at constant pH (9.04), ionic strength ($\mu = 0.4$) and temperature (60 ± 0.2 °C), varying only the buffer concentration. The results showed no significant effect on the degradation of avobenzone for buffer species used in the study. The effect of ionic strength on the decomposition of avobenzone was also studied by keeping the buffer concentration (0.1 mol/L), pH (7.41) and temperature (60 ± 0.2 °C) constant and varying only ionic strength by addition of different amounts of KCl. The results indicate no kinetic salt effect for the degradation of avobenzone. Table 2 summarises the effects of buffer species and ionic strength on avobenzone degradation. The effect of temperature on the decomposition of avobenzone was determined by measuring the first-order rate

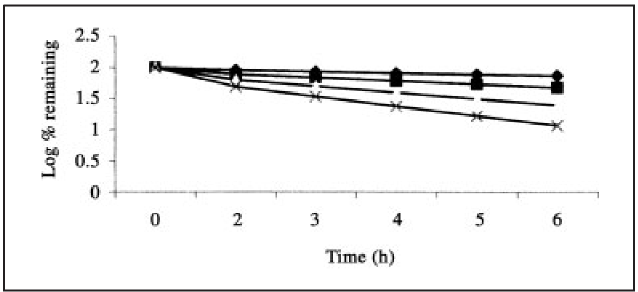

Fig. 1: Plot of logarithm of percent remaining of avobenzone against time. pH 7.41 ■—■ pH 8.00 ■—■ pH 9.04 ▲—▲ pH 10.02 ×—×

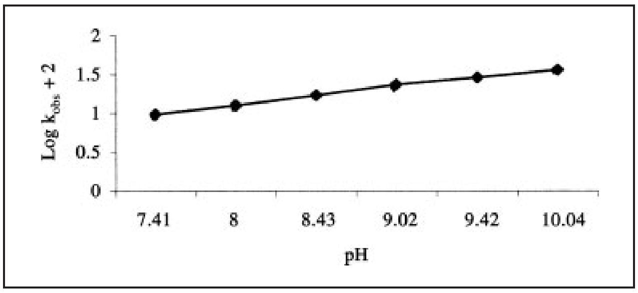

Fig. 2: Plot of logarithm of rate constant against pH

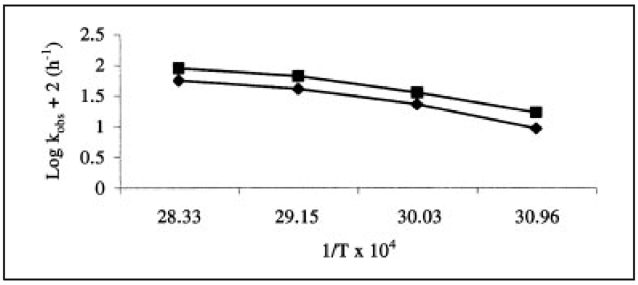

Fig. 3: Plot of logarithm of rate constant against reciprocal of absolute temperature
pH 9.04 ■——■ pH 10.02 ■——■

constants at pH 9.04 and 10.02 respectively, constant ionic strength ($\mu = 0.4$) and at temperature ranging from 50 to 80 °C. The results are presented in Table 3. A plot of the logarithm of the observed first-order rate constant versus the reciprocal of the absolute temperature is shown in Fig. 3. The Arrhenius plots were linear ($R^2 > 0.98$), indicating that the degradation mechanism was not with a change in temperature inside the temperature range investigated. Using the Arrhenius equation, the activation energy for the hydrolytic reaction was evaluated. The estimated activation energies are 56.2 kJ/mol (pH 9.04) and 52.6 kJ/mol (pH 10.02) respectively. Arrhenius equation was also used to predict rate constants at room temperature (25 °C) for both pH values. The rate constants obtained at 25 °C are 0.0187/h (pH 9.04) and 0.0363/h (pH 10.02) respectively. Estimated frequency factors at 25 °C are 1.3×10^8/h (pH 9.04) and 5.9×10^7/h respectively. The high values of the frequency factors indicate a large proportion of collisions between avobenzone molecules and hydroxide ions during the degradation reactions. The values also show that more effective collisions occurred at pH 9.04 than pH 10.02. Half-lives calculated at 25 °C are 37 h (pH 9.04) and 19 h (pH 10.02) respectively. This study made no attempt to indicate if the degraded products are the intermediates or final products. A plausible reaction mechanism of the hydrolysis is a nucleophilic attack by the hydroxide ion on one of the carbonyl groups in avobenzone structure and the subsequent cleavage of the bond between the generated carboxyl group and methylene group to give *p*-methoxy benzoic acid and *p*-butylphenylacetone.

Table 1: First-order rate constant of avobenzone degradation in aqueous solutions

pH	Medium	k_{obs} (h^{-1})	t½ (h)
2.03	Hydrochloric acid	–	–
3.01	Hydrochloric acid	–	–
7.41	Phosphate buffer	0.0970 ± 2.94	7.1
8.00	Borate buffer	0.1253 ± 3.93	5.5
8.43	Borate buffer	0.1692 ± 2.74	4.1
9.04	Borate buffer	0.2336 ± 2.09	3.0
9.42	Borate buffer	0.2863 ± 1.03	2.4
10.02	Borate buffer	0.3395 ± 2.17	2.0

Table 2: Effect of buffer concentration and ionic strength on first-order rate constant

Buffer concentration		Ionic strength	
(mol/L)[a]	k_{obs}[c] (h^{-1})	KCl (mol/L)[b]	k_{obs}[c] (h^{-1})
0.050	0.2319 ± 2.36	0.200	0.0962 ± 3.07
0.100	0.2294 ± 3.10	0.400	0.0970 ± 3.97
0.150	0.2328 ± 2.27	0.600	0.0951 ± 2.68
0.200	0.2289 ± 2.74	0.800	0.0959 ± 2.89

[a] 60 ± 0.2 °C, pH 9.04 H_3BO_3–NaOH–KCl
[b] 60 ± 0.2 °C, pH 7.41; NaOH–KH_2PO4
[c] Mean ± RSD (%), n = 3

Table 3: Effect of temperature on the rate constant of avobenzone

pH	Temperature, °C	k_{obs} (h^{-1})	t½ (h)
9.04	25	0.0187	37.1
	50	0.0933	7.4
	60	0.2336	3.0
	70	0.4129	1.7
	80	0.5648	1.2
10.02	25	0.0363	19.1
	50	0.1687	4.1
	60	0.3595	1.9
	70	0.6650	1.0
	80	0.8928	0.78

The breakdown of avobenzone was observed to follow first-order kinetics and the reaction was hydroxide ion catalyzed decomposition. Buffer concentration or ionic strength had no effect on the rate constant. Half-lives were calculated from the rate constants obtained using Arrhenius equation. Finally, the estimated half-lives at 25 °C suggest that avobenzone can possess high stability in sunscreen cosmetic products, if proper storage conditions are maintained.

3. Experimental

3.1. Materials

Avobenzone (DMS Nutritional Products Inc., USA), and all the organic solvents used were of HPLC grade (Fisher Scientific, USA).

3.2. Equipment

All separations were carried out with Hitachi LC 6200 pump and AS 2000 autosampler injector (Hitachi Co., Japan), Kratos Spectroflow 783 detector (Spectra Physics, USA) and Zorbax analytical column C18, 150 × 4.6 mm, 3.5 μm (Agilent Technologies, USA).

3.3. Chromatographic procedure

The mobile phase consisted of methanol : 0.1% phosphoric acid (85 : 15, V/V). The flow rate was controlled at 1 ml/min at 35 °C. The injection volume was 10 μl and the effluent was detected at 310 nm.

3.4. Buffer solutions

The buffer solutions used for the kinetic study: KCl–HCl. pH 2–3; NaOH–KH_2PO_4, pH 7.4; H_3BO_3–NaOH–KCl, pH 8–10. Constant ionic strength (μ) of 0.4 mol/L was maintained for each buffer by adding calculated amount of KCl.

3.5. Kinetic measurement

The rate studies were performed in buffer solutions at 60 ± 0.2 °C. The effect of temperature on the hydrolytic reaction of avobenzone was determined at temperatures ranging from 50 to 80 °C. The total buffer concentration was 0.1 mol/L, and a constant ionic strength of 0.4 mol/L was maintained for each buffer by adding a calculated amount of potassium chloride. Stock solution of avobenzone (4 mg/ml) was prepared in methanol. The stock solution was diluted with each buffer solution to give a concentration of 160 μg/ml. The solutions were kept in a water bath and at appropriate intervals, aliquots were withdrawn and injected into the chromatograph. The rate constants were determined from the slopes of linear plots of logarithm of percent remaining versus time.

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