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Determination of Rate Constants and Inhibition Coefficients of the Stabilizer SO-3 and Functional Derivatives of the ω-(4-Hydroxyaryl)alkyl Series

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Abstract—Antioxidative properties of ten inhibitors of the ω-(4-hydroxyaryl)alkyl type were studied in a model reaction of the initiated oxidation of ethyl oleate in chlorobenzene. The rate constants k_7 and the inhibition coefficients f were determined. All studied inhibitors are characterized by close values of the k_7 constants, $(2.6–3.7) \times 10^4$ l mol^{-1} s^{-1}, but differ in the values of inhibition coefficients. A relationship between the structures of the test compounds and their inhibiting activity is discussed.

INTRODUCTION

Bis[3-(3',5'-di-*tert*-butyl-4'-hydroxyphenyl)propyl] sulfide (antioxidant SO-3) is a highly efficient thermal stabilizer of polymeric composites based on polyethylene and polypropylene. It surpasses such antioxidants as Ionol, Santonox, and TB-3 in inhibiting properties [1, 2]. Since SO-3 is not toxic, it can be used in the production of consumer goods [3, 4]. It may also be used as an antioxidant for fat-containing food products and fat-soluble drugs [5–7]. The high efficiency of the SO-3 antioxidant is related to the bifunctional character of its antioxidant activity and internal synergistic effect [8]. However, up to now, the antiradical activity of SO-3 has not been characterized quantitatively. In this work, we determined the rate constants k_7 and the inhibition coefficients f of the SO-3 stabilizer and its structural analogs using a model reaction of the inhibited oxidation of ethyl oleate initiated by azobisisobutyronitrile (AIBN) in chlorobenzene [9, 10].

In the presence of a phenol antioxidant, the simplest scheme of AIBN-initiated oxidation can be represented as follows [11]:

Chain initiation

$$\text{AIBN} \longrightarrow r^{\bullet} \xrightarrow{+\text{RH}} \text{R}^{\bullet}, \quad w_{\text{i}} \qquad (0)^1$$

Chain propagation

$$\text{R}^{\bullet} + \text{O}_2 \longrightarrow \text{RO}_2^{\bullet}, \quad k_1$$

$$\text{RO}_2^{\bullet} + \text{RH} \longrightarrow \text{ROOH} + \text{R}^{\bullet}, \quad k_2 \qquad \text{(II)}$$

Chain termination

$$\text{RO}_2^{\bullet} + \text{RO}_2^{\bullet} \longrightarrow \text{molecular products}, \quad k_6$$

$$\text{InOH} + \text{RO}_2^{\bullet} \longrightarrow \text{ROOH} + \text{InO}^{\bullet}, \quad k_7 \qquad \text{(VII)}$$

$$\text{RO}_2^{\bullet} + \text{InO}^{\bullet} \longrightarrow \text{molecular products}, \quad k_8 \qquad \text{(VIII)}$$

$$\text{InO}^{\bullet} + \text{InO}^{\bullet} \longrightarrow \text{molecular products}, \quad k_9, \qquad \text{(IX)}$$

where $r^{\bullet}$ is the radical formed from the initiator; RH is a hydrocarbon; $\text{R}^{\bullet}$ and $\text{RO}_2^{\bullet}$ are alkyl and peroxy radicals, respectively; InOH is the phenol inhibitor; $\text{InO}^{\bullet}$ is the inhibitor radical; w_{i} is the rate of chain initiation; and k_{i} are the rate constants of the corresponding reactions.

If the inhibitor substantially decreases the oxidation rate, the rate of reaction (VII) is much higher than the rate of reaction (VI) and the quadratic chain termination by reaction (VI) can be neglected. In this case, in a quasi-steady-state approximation with respect to radicals, under the condition of long chains, the following expression is valid for the reaction rate:

$$-\frac{\text{d}[\text{O}_2]}{\text{d}t} = w_{\text{i}}\frac{k_2[\text{RH}]}{fnk_7[\text{InOH}]}, \qquad (1)$$

where f is the inhibition coefficient, which is equal to the number of chains terminated by one phenoxy group of the inhibitor (depending on the ratio between the rates of reactions (VIII) and (IX), it can vary from 1 to 2 [12]), n is the number of phenoxy groups in the inhibitor molecule and $\text{d}[\text{O}_2]$ is the amount of oxygen

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[1] The commonly accepted numeration of the reactions is used.

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(in mol) consumed for time dt per the overall volume of the sample (in l).

If the inhibitor is consumed only in chain termination reactions, at a constant initiation rate w_i, the time of its action (induction period) τ is determined by the relation

$$\tau = \frac{fn[\mathrm{InOH}]_0}{w_i}, \tag{2}$$

where $[\mathrm{InOH}]_0$ is the initial concentration of the inhibitor.

Equation (2) can be used for finding the f coefficient from the experimental induction period and for measuring the rate of initiation (inhibitor method).

At any point in time t ($t < \tau$), we can write

$$fn([\mathrm{InOH}]_0 - [\mathrm{InOH}]) = w_i t. \tag{3}$$

Inserting the expression for [InOH] from (3) and $[\mathrm{InOH}]_0$ from (2) into (1) and integrating the resulting equation for low conversions ($[\mathrm{RH}] \cong [\mathrm{RH}]_0$), we obtain the following relationship:

$$\frac{\Delta[\mathrm{O_2}]}{[\mathrm{RH}]} = -\frac{k_2}{k_7}\ln\left(1 - \frac{t}{\tau}\right), \tag{4}$$

where $\Delta[\mathrm{O_2}]$ is the volume of absorbed oxygen referred to the sample volume, mol/l.

Using experimental values of τ and $\Delta[\mathrm{O_2}]$, we can find the k_2/k_7 ratio from Eq. (4). When the constant k_2 is known, the inhibition rate constant k_7 can also be determined. The value of k_7 is calculated per inhibiting phenoxy group of the antioxidant.

EXPERIMENTAL

Ethyl oleate (Acros Organics, USA) was oxidized in chlorobenzene (the ethyl oleate to chlorobenzene volume ratio was 1 : 1) at 60°C. AIBN (Acros Organics) was successively recrystallized from ethanol and benzene [13]. The initiation rate $w_i = 8.4 \times 10^{-7}$ mol l^{-1} s^{-1} was determined by the inhibitor method from the induction period τ using Eq. (2); Ionol with the inhibition coefficient $f = 2$ [10] was used as an antioxidant. The volume of consumed oxygen was measured volumetrically according to a published procedure [13]. The $\mathrm{O_2}$ pressure in the system was 1 atm, and the volume of the oxidized mixture was 5 ml (25°C). The induction period was determined graphically as the coordinate of the intersection point of two tangents to the kinetic curve; the slopes of the tangents were 0.5 and 0.75 of the slope of the straight line of the uninhibited reaction [13].

The following inhibitors were used: 2,6-di-*tert*-butyl-4-methylphenol (Ionol) (Russia); 2-(3',5'-di-*tert*-butyl-4'-hydroxyphenyl)-1-ethanol (**Ia**), 3-(3',5'-di-*tert*-butyl-4'-hydroxyphenyl)-1-propanol (**Ib**), 4-(3',5'-di-*tert*-butyl-4'-hydroxyphenyl)-1-butanol (**Ic**), and 3-(3',5'-di-*tert*-butyl-4'-hydroxyphenyl)-1-butanol (**Id**) prepared at the Vorozhtsov Institute of Organic Chemistry, Siberian Division, Russian Academy of Sciences; 2-(3',5'-di-*tert*-butyl-4'-hydroxyphenyl)-1-chloroethane (**IIa**), 3-(3',5'-di-*tert*-butyl-4'-hydroxyphenyl)-1-chloropropane (**IIb**), 3-(3'-*tert*-butyl-4'-hydroxyphenyl)-1-chloropropane (**IIe**), bis[2-(3',5'-di-*tert*-butyl-4'-hydroxyphenyl)ethyl] sulfide (**IIIa**), bis[3-(3',5'-di-*tert*-butyl-4'-hydroxyphenyl)propyl] sulfide (SO-3), and bis[3-(3'-*tert*-butyl-4'-hydroxyphenyl)propyl] sulfide (**IIIe**) synthesized at the Novosibirsk State Pedagogical University according to procedures developed previously [14–17]. The purity of the test samples was 97–99% according to GLC data.

RESULTS AND DISCUSSION

The initial portions of the kinetic curves of oxygen consumption are adequately linearized in the coordinates of Eq. (4) for all inhibitors. This fact indicates that the oxidation of ethyl oleate in chlorobenzene is inhibited according to the above scheme and the quantitative characteristics of the antiradical activity of inhibitors (rate constants k_7 and inhibition coefficients f) can be determined by Eqs. (2) and (4).

The kinetic curves of oxygen consumption and their anamorphoses in the coordinates of Eq. (4) for Ionol and the SO-3 stabilizer are presented in the figure. The k_2/k_7 ratios were determined by the slopes ($\tan\beta$) of straight lines in the coordinates $\Delta[\mathrm{O_2}]/[\mathrm{RH}]$ vs. $-\ln(1 - t/\tau)$. According to published data [10], under the model conditions considered, $k_7 = (2.6 \pm 0.4) \times 10^4$ l mol^{-1} s^{-1} for Ionol. This made it possible to estimate the k_2 value from the relation $k_2 = k_7 \tan\beta$, where k_7 is the inhibition rate constant for Ionol.

The determined values of the constants k_7 and coefficients f (with root-mean-square errors) are presented in the table. These data show that all test compounds are characterized by similar values of the k_7 rate constants close to k_7 of Ionol. However, their inhibition coefficients f are lower than that of Ionol. The value of $f = 2$ for Ionol shows that, under the model conditions considered, at the end of the induction period of oxidation, the phenoxy radicals of Ionol formed in reaction (VII) were quantitatively consumed in reactions (VIII) and (IX). The SO-3 antioxidant and the other test inhibitors of the ω-(3,5-di-*tert*-butyl-4-hydroxyphenyl)alkyl type were characterized, under the same conditions, by shorter (compared to Ionol) induction periods τ and hence by lower inhibition coefficients f. This fact indicates a lower activity of the phenoxy radicals in reactions (VIII) and (IX). This is consistent with published data [18], according to which the induction

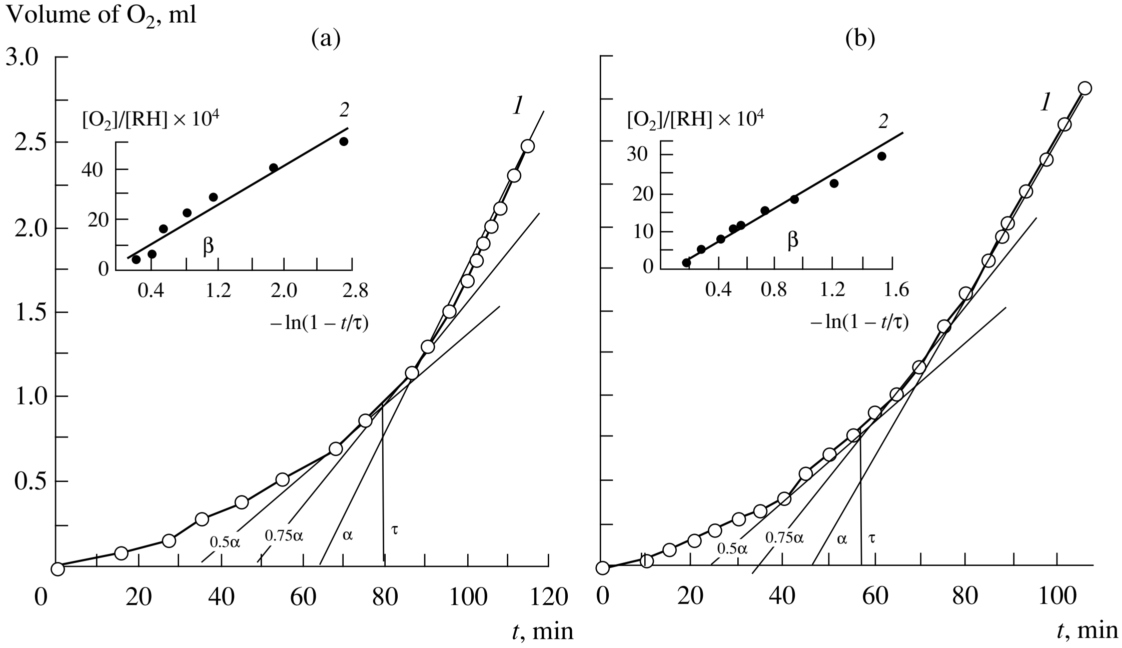
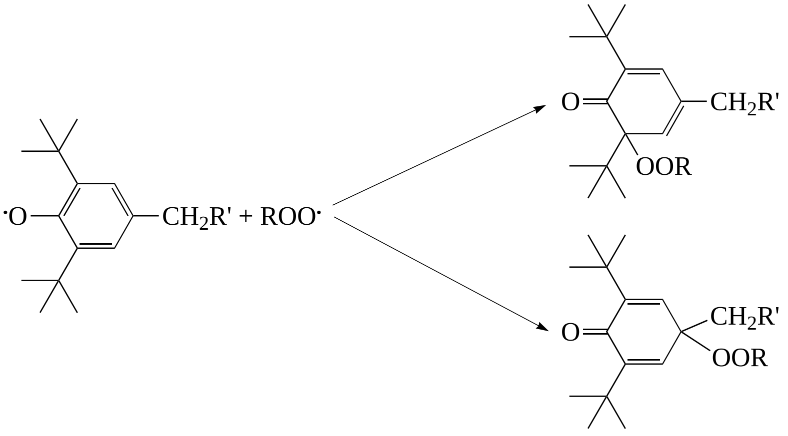


Fig. 1. (*1*) Kinetic curves of oxygen consumption and (*2*) their anamorphoses in the coordinates of Eq. (4) for the initiated oxidation of ethyl oleate in chlorobenzene in the presence of (a) Ionol and (b) the SO-3 stabilizer as inhibitors. [PhOH] = 2×10^{-4} mol/l; 60°C.

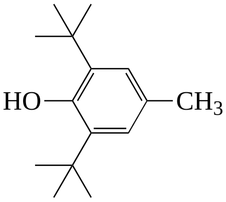
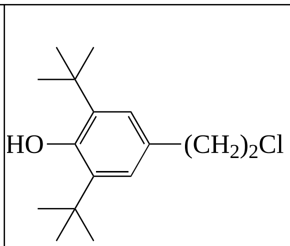
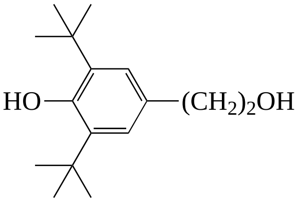
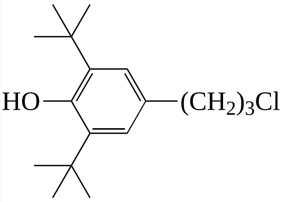
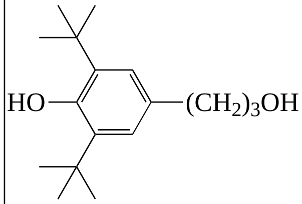
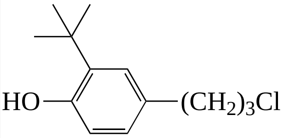
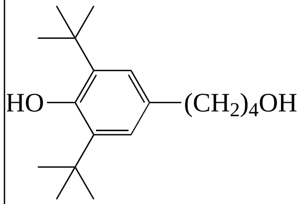
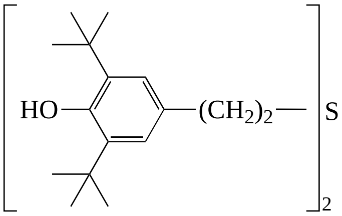
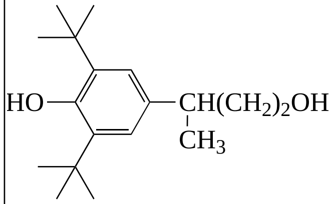
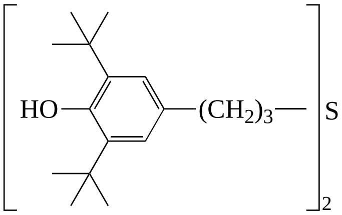
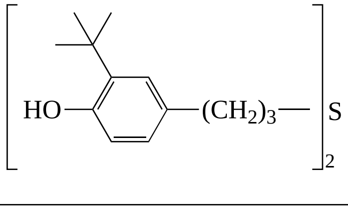
period exhibited by ω-(3,5-di-*tert*-butyl-4-hydroxyphenyl)alkanols and 3-(3',5'-di-*tert*-butyl-4'-hydroxyphenyl)propionic acid derivatives in the model reaction of polybutadiene self-oxidation (130°C) is shorter than that of Ionol by a factor of 1.1–1.6.

According to the spin density distribution in the phenoxy $PhO^{\bullet}$ radical, the $RO_2^{\bullet}$ peroxy radical can be added at the *ortho*- and *para*-positions of a phenol ring in reaction (VIII) to form isomeric quinoid peroxide species as follows:

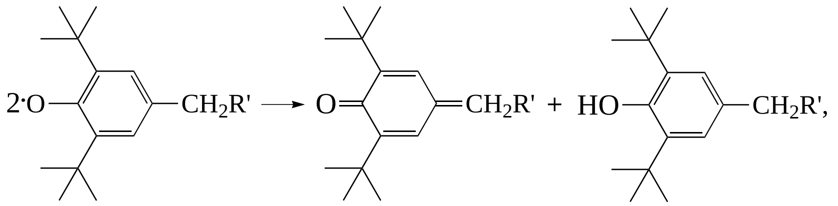


Because bulky *tert*-butyl groups sterically hinder the formation of the *ortho* quinoid peroxide, we can expect the addition of $RO_2^{\bullet}$ at the *para*-position to be more probable for Ionol and other 4-alkyl-substituted 2,6-di-*tert*-butylphenols. Among the test inhibitors, alkanol **Id** with a *sec*-alkyl substituent—which creates steric shielding of the *para*-position of the phenol ring—chloroalkane **IIa**, and sulfide **IIIa** are characterized by the lowest inhibition coefficients. The coefficient *f* increases in the order **Ia**–**Ib**–**Ic** and on going from **IIa** to **IIb** and from **IIIa** to **IIIb**. This corresponds to the removal of a heteronuclear substituent from the aromatic ring.

Rate constants k_7 and inhibition coefficients *f* of the test inhibitors in ethyl oleate oxidation in chlorobenzene at 60°C

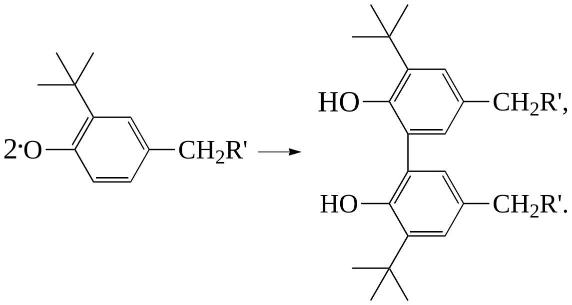
Antioxidant		$k_7 \times 10^{-4}$, l mol^{-1} s^{-1}	*f*	Antioxidant		$k_7 \times 10^{-4}$, l mol^{-1} s^{-1}	*f*
Ionol		2.60 ± 0.40	2.0	**IIa**		3.12 ± 0.42	1.1 ± 0.1
Ia		2.63 ± 0.07	1.3 ± 0.2	**IIb**		2.84 ± 0.90	1.4 ± 0.1
Ib		3.30 ± 0.32	1.4 ± 0.1	**IIe**		2.71 ± 0.43	1.8 ± 0.1
Ic		2.83 ± 0.21	1.6 ± 0.1	**IIIa**		3.58 ± 0.85	1.0 ± 0.2
Id		3.53 ± 0.35	1.0 ± 0.2	SO-3		2.78 ± 0.14	1.4 ± 0.1
				IIIe		3.01 ± 0.13	1.3 ± 0.1

The structure of the *para*-alkyl substituent in the test inhibitors can also affect the bimolecular decay of $InO^{\bullet}$. For 2,6-di-*tert*-butyl-4-alkylphenols, this process occurs as the disproportionation



(IX)

whereas with 2-*tert*-butyl-4-alkylphenols, the following dimerization reaction additionally takes place:



(IXa)

Reaction (IX) assumes a radical attack on the α-C atom of the *para*-alkyl substituent, and the phenoxy radicals of Ionol, which bear methyl groups at the *para*-position, manifest a higher activity in this reaction than that of phenoxy radicals formed by other test inhibitors.

A relatively high value of the inhibition coefficient for monodealkylated chloroalkane **IIe** can be due to the participation of its phenoxy radicals in reaction (IXa). Similar transformations for the phenoxy radical of the corresponding sulfide **IIIe** are less probable due to their larger sizes and higher molecular weights.

Thus, our experimental data indicate that the SO-3 stabilizer and the functional derivatives of the ω-(4-hydroxyaryl)alkyl series are characterized by similar rate constants of inhibition ($(2.63–3.58) \times 10^4$ l mol^{-1} s^{-1}), which are close to the inhibition rate constant of Ionol ($(2.6 \pm 0.4) \times 10^4$ l mol^{-1} s^{-1}). However, their inhibition coefficients *f* are lower than that of Ionol. The distinctions in the antiradical activity of the test compounds can be interpreted by the commonly accepted mechanism of the antioxidative action of phenol antioxidants.

REFERENCES

1. RF Patent 1072420, 1994.
2. RF Patent 1007405, 1993.
3. Sorokina, I.V., Lapik, A.S., Dolgikh, M.P., and Popova, L.P., *Izv. Akad. Nauk SSSR, Sib. Otd., Ser. Biol.*, 1986, no. 1, p. 123.
4. Sheftel', V.O., *Vrednye veshchestva v plastmassakh. Spravochnik* (Hazardous Substances in Plastics: A Handbook), Moscow: Khimiya, 1991.
5. Rezvukhin, A.I., Krysin, A.P., and Shalaurova, I.Yu., *Vopr. Med. Khim.*, 1995, no. 3, p. 37.
6. Voevoda, T.V., Tolstikova, T.G., Sorokina, I.V., *et al.*, *Eksp. Klinich. Farmakol.*, 2000, vol. 63, no. 4, p. 57.
7. Orlova, T.N., Tolstikova, T.G., Sorokina, I.V., *et al.*, *Khim. Farm. Zh.*, 2000, vol. 34, no. 9, p. 9.
8. Prosenko, A.E., *Cand. Sci. (Chem.) Dissertation*, Novosibirsk: Novosibirsk State Pedagogical Univ., 2000.
9. Roginskii, V.A., *Kinet. Katal.*, 1990, vol. 31, no. 3, p. 546.
10. Kadochnikova, G.D., *Svobodno-radikal'noe okislenie lipidov v eksperimente i klinike* (Free-Radical Oxidation of Lipids in Experiment and Clinic), Tyumen': Izd-vo Tyumen. Gos. Universiteta, 1997, part 1, p. 21.
11. Roginskii, V.A., *Fenol'nye antioksidanty. Reaktsionnaya sposobnost' i effektivnost'* (Phenol Antioxidants: Reactivity and Effectiveness), Moscow: Nauka, 1988.
12. Tsepalov, V.F., Kharitonova, A.A., Gladyshev, G.P., and Emanuel', N.M., *Kinet. Katal.*, 1977, vol. 18, no. 5, p. 1261.
13. Tsepalov, V.F., *Issledovanie sinteticheskikh i prirodnykh antioksidantov in vivo i in vitro* (Study of Synthetic and Natural Antioxidants *in vivo* and *in vitro*), Moscow: Nauka, 1992, p. 16.
14. RF Patent 1162781, 1993.
15. RF Patent 1376511, 1993.
16. Prosenko, A.E., Dyubchenko, O.I., and Krysin, A.P., *Tez. dokl. reg. konf. "Perspektivy razvitiya malotonnazhnoi khimii"* (Abstracts of Regional Conf. "Prospects of the Development of Small-Scale Chemistry"), Krasnoyarsk, 1989, p. 22.
17. RF Patent 1658601, 1993.
18. Ershov, V.V., Piotrovskii, K.B., Tupikina, N.A., *et al.*, *Izv. Akad. Nauk SSSR, Ser. Khim.*, 1976, no. 5, p. 1174.