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The viscosity of nematic liquid crystals

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ABSTRACT. A simultaneous examination of data on the dynamic, kinematic, and rotational viscosities of nematic liquid crystals (NLC) belonging to 320 chemical classes has been carried out for the first time. The methods for the measurement of the viscosities of the NLC have been subjected to a comparative analysis and the limits of applicability of different procedures for the description of their temperature variation are discussed. The tables present data permitting the calculation with satisfactory accuracy of the viscosities of the majority of mesogenic substances at any temperature in the nematic range. The influence of the molecular structure of the NLC on the viscosities and on their temperature variation has been analysed and information is presented about the viscosities of the Soviet and foreign liquid crystal materials used in practice.

The bibliography includes 158 references.

Contents

I. Methods for the measurement of the viscosities of nematic liquid crystals 917
II. Temperature variation of the viscosities of nematic liquid crystals 918
III. Tables of the viscosities of nematic liquid crystals 919
IV. Relation between the molecular structure of nematic liquid crystals and their viscosity 938

By virtue of their unique optical properties and low energy consumption, nematic liquid crystals (NLC) have now found wide scale applications in devices for the treatment and representation of information. One of the important characteristics of NLC, which determines the rapidity of their response in the working temperature range, is their viscosity. Both the dynamic viscosity η (or the kinematic viscosity ν), describing the flow of liquid in the nematic and isotropic phases, and the rotational viscosity γ_1, which has no analogue in isotropic liquids and is related to the dissipation of energy on reorientation of the NLC director (the director is a unit vector indicating the direction of the long axes of the NLC molecules), are measured for NLC. The communications by Benicewicz and Johnson[1] and de Gennes[2] are devoted to the viscosity of liquid crystals (LC) but the data presented there are too limited to permit a discussion not only of the relation between the viscosity and the molecular structure of NLC but also of the form of the temperature variation of the viscosity, the knowledge of which is essential for the development of LC materials with a satisfactory fast response at low temperature.

This review gives for the first time a systematic account of data concerning the relation between the chemical structure of NLC and their viscosity, the temperature variation of the viscosity of different NLC being considered from a single standpoint. The tabulated data are of interest for specialists dealing with liquids and may serve as a basis for specific investigations and the search for new nematic, smectic, polymeric, and lyotropic liquid crystals.

I. Methods for the measurement of the viscosities of nematic liquid crystals

Only the dynamic (η) or kinematic [$\nu = \eta/\rho$ (ρ is the density of the NLC)] viscosities are usually measured for many liquid crystals. However, in the present study attention is concentrated on the rotational viscosity γ_1, which determines the time of the electro-optical response. It has been shown[3,4] that there is a relation between the rotational viscosity γ_1 and the viscosity measured by capillary methods, described approximately by the relation

$$\gamma_1 \simeq a\eta + b, \tag{1}$$

$$\gamma_1 \simeq a(\eta_3 - \eta_2) + b, \tag{2}$$

where a and b are weakly temperature dependent coefficients and η_2 and η_3 are the Miesowicz viscosity coefficients.[2] These relations are confirmed by the simultaneous measurements of the viscosities γ_1 and η or η_2 and η_3 for a set of NLC belonging to different chemical classes.[4,5] For comparison, the tables indicate in a number of instances the values of γ_1 and η as well as the ratio γ_1/η.

Depending on the type of viscometer, the dynamic viscosity η (Ubbelohde viscometer) or the kinematic viscosity ν (Ostwald viscometer) is measured. Novel methods have been developed for the measurement of the rotational viscosity γ_1. They reduce to one of three types: the rotating magnetic field method, the dynamics of the Fredericks transition, and the spectrum of the light scattered by the thermal fluctuations of the director.

In the first method, the rotation of the magnetic field leads to the rotation of the NLC director, the second rotation occurring with a phase delay at sufficiently low angular velocities.[2,6] Having measured this delay, for example, with the aid of a torsional balance,[7] it is possible to determine the quantity γ_1/ρ or γ_1/χ_a (χ_a is the anisotropy of the diamagnetic permeability). The errors arising in this method of measurement have been studied in detail.[7] In order to measure γ_1 to within 0.1%, approximately 60 cm^3 specimens have been used,[4,7] which is by no means always possible especially in the study of new substances. The reduction of the volume of the specimen leads as a rule to an unduly low value of the measured quantity (compare, for example, the studies of Kneppe et al.[4] and Siedler et al.[8]).

An appreciably smaller amount of substances (less than 30 mg) is required in the measurement of γ_1 on the basis of the dynamics of the Fredericks transition. In this case the ratio γ_1/K_{22}[9] or η_S/K_{11}[10,11] is determined from the characteristic relaxation time (K_{11} and K_{22} are the elasticity coefficients of the NLC, $\eta_S = \gamma_1 - \alpha_3^2/\eta_2$ is the

viscosity describing the rate of relaxation of the transverse bending deformation, and α_3 is the Leslie viscosity coefficient). In the direct measurement of γ_1/K_{22}, one investigates the time variation of the location of the conoscopic figure formed when a convergent light beam is passed through a liquid crystal cell in a longitudinal magnetic field (the field is parallel to the supports but is at right angles to the director). Owing to the difficulty of determining the angle of rotation of the conoscopic figure and of K_{22}, this method has not come to be widely used. The method of measurement of η_S/K_{11} based on the optical[10] or capacitative[11] response of a planarly oriented cell after a transverse electric field has been switched off, has come to be more widely used. Since $|\alpha_3| \ll \gamma_1, \eta_1$,[12] the relation $\eta_S \simeq \gamma_1$ holds to within 1–2%, which is better than the accuracy of the measurement of η_S by this method (to within 7–10%). Simultaneously with γ_1, it is possible to measure in this cell the double refraction Δn and the elasticity coefficient K_{11} (when the dielectric anisotropy $\Delta\varepsilon$ is known). A method for the measurement of γ_1, based on the relaxation of the deformation of a specimen placed in a strong magnetic field (up to 0.8 T), has been described.[13] Its accuracy is to within 6%. It suffers from the disadvantage that the quantity χ_a has to be known.

The thermal fluctuations of the liquid crystal director lead to light scattering, which greatly exceeds that in isotropic liquids. The viscoelastic ratio γ_1/K_{22} or η_S/K_{11} can be determined from the half-width of the scattering spectrum and, knowing the intensity of the scattered light and of the refractive index of the NLC, the viscosity γ_1 or η_S itself can be determined.[2,14,15] Because of the need to view the light scattering at low angles where there is an appreciable contribution due to scattering by inhomogeneities in the orientation of the liquid crystal, the direct measurement of γ_1 is difficult or altogether impossible. The quantity η_S/K_{11} is therefore usually measured for the following geometry of the observation: the polarisation of the incident light is parallel to the director and perpendicular to the polarisation of the scattered light, while the scattering angle is 30–40°.[14] Although the corresponding method is fairly complex (the optical mixing spectroscopy and the correlation of single signals are needed), it has a significant advantage, namely the absence of are needed), it has a significant advantage, namely the absence of deformation of the specimen, which is important in the study of NLC with a strong transverse intermolecular interaction.

The tabulated γ_1 have been obtained using all the principal methods. It has been shown[16] that the results of the measurement of γ_1 by different methods agree well.

II. Temperature variation of the viscosities of nematic liquid crystals

The temperature variation of the viscosity of an isotropic liquid is usually described satisfactorily by the Arrhenius law:

$$\eta = a \exp(E/kT), \tag{3}$$

where a is a constant, E the activation energy, k the Boltzmann constant, and T the temperature. On the assumption that there is no intermolecular interaction, this relation is described by the Fulcher–Tammann formula:

$$\eta = b \exp[B/(T-T_0)], \tag{4}$$

where b and B are constants, $(T - T_0)/B$ is the fluctuation free volume, $T_0 \simeq T_g + 50$, and T_g is the glass point of the liquid. A dependence on the order parameter S is introduced into the pre-exponential factor in order to describe the variation of the viscosity γ_1 near the NLC–isotropic liquid transition temperature T_{NI}:

$$\gamma_1 = aS^x \exp(E/kT). \tag{5}$$

It has been shown[16] that $x = 1$ for liquid crystals with an elongated conjugation chain (biphenyls, phenylpyrimidines, phenyl benzoates, etc.), while $x = 2$ for liquid crystals whose molecules contain a fragment with saturated bonds (phenylcyclohexanes, phenylbicyclooctanes, etc.).

The limits of applicability of the activation and free volume models have been found.[17] The former is valid for all NLC with a small mesophase range (up to 40°) at temperatures $T > 20$ °C, while the latter is valid for NLC with a low activation energy ($E < 0.45$ eV = 4.95×10^3 Å) and also for NLC with an appreciable (above 60°) mesophase range extending to the region of reduced temperatures (as far as 0 °C and below). In the same study, it was shown that the viscosity γ_1 is determined by the molecular packing density, its temperature variation [the activation energy in Eqn. (5)] is determined by the intermolecular interaction energy, the order of magnitude of which is equal to that of the enthalpy of fusion of the NLC and is determined by the presence or absence of a fragment with saturated bonds (a cyclohexane or bicyclooctane fragment).

A theoretical description of the temperature variation of the rotational viscosity on the basis of a molecular-statistical approach, combining the characteristics of the activation and free volume models, has been proposed:[18]

$$\gamma_1(T, S) = gS^2 \exp[\varepsilon S/kT + \theta S^2/(T-T_0)], \tag{6}$$

where g is a weakly temperature dependent parameter, εS the height of the Maier–Saupe potential, θ a parameter determined by physical properties, and T_0 the temperature at which the motion of the director is frozen; in fitting the $\gamma_1(T, S)$ relation for any substance, the first or second term in the argument of the exponential function is neglected. The choice of the fitting procedure is determined by the width of the nematic range.

A comparative mathematical analysis of the suitability of different models for the description of the dependence of the rotational viscosity on temperature and the order parameter has been carried out.[16,17] The best agreement between the calculated curves and the experimental points and the highest correlation coefficients have been obtained for the majority of substances when the $\gamma_1(T)$ relation is described by an equation type (5). For certain cyclohexane and bicyclooctane derivatives, the smallest deviation was obtained when the results were fitted on the basis of the free volume model taking into account the order parameter S. Equations of type (6) as a rule give rise to a poorer agreement with experimental results although it has been noted[17] that the theory[18] makes it possible to explain the change in γ_1 in the homologous series of liquid crystal substances and the proportionality $E \propto T_{NI}$ for substances with a similar type of intermolecular interaction.

In most cases the experimental relations have therefore been fitted by curves of type (5) taking into account the specific molecular structure of the substance ($x = 1$ or 2). For a number of substances, the values of S were not available but the double refractions Δn were known, which made it possible to use analogous fitting procedures, because $\Delta n \propto S$.[2,16] In the absence of data making it possible to infer the temperature variation of the order parameter S, a simple equation of type (3) was fitted. For certain cyclohexane and bicyclooctane derivatives, a fitting procedure corresponding to the free volume model with allowance for the variation of S was employed.

Overall, in the tables an attempt has been made to analyse the temperature variations of the rotational viscosities of NLC belonging to different chemical classes using a single approach to their description. The relations were fitted on the basis of data presented in the tables or figures in the original publications. Only in certain cases (as a rule when the values of γ_1 or η were quoted at only one temperature) was an additional mathematical treatment of the original results not carried out.

III. Tables of the viscosities of nematic liquid crystals

The tables are constructed so that the values of γ_1 (or η and ν) can be obtained from the parameters listed in them at any temperature at which the given substance is nematic. Apart from specially stipulated cases, all the equations fitted were of the Arrhenius type:

$$\ln A = \ln A_0 + E/T. \qquad (a, b, c)$$

In equation (*a*) the letter A denotes the rotational viscosity γ_1 or its kinematic analogue γ_1/ρ (ρ is the density of the NLC) and also the dynamic viscosity η or the kinematic viscosity $\nu = \eta/\rho$. In the description of the temperature variation of the rotational viscosity by means of formula (*b*), the letter A denotes the ratio γ_1/S or $\gamma_1/\Delta n$ (account is taken of the proportionality $\Delta n \propto S$), whereas in the case where formula (*c*) is fitted A denotes the ratio γ_1/S^2 or $\gamma_1/(\Delta n)^2$. The viscosity is expressed in IS units: in 0.1 Pa s = 1 P (γ_1, η) or in 10^{-4} m^2 s^{-1} = 1 Stokes (γ_1/ρ, ν).

Table 1. The viscosities of nematic liquid crystals.

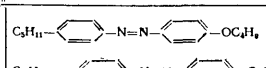
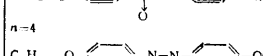
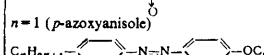
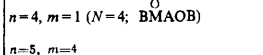
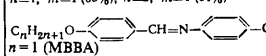
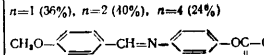
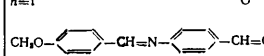
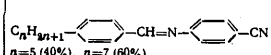
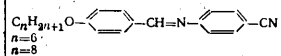
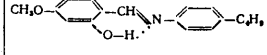
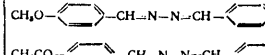
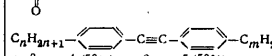
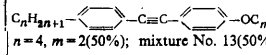
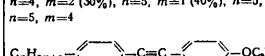
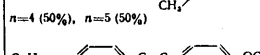
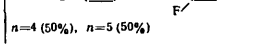
No. of compound	Name	Structural formula	Fitting formula	Viscosity*[1], 10^{-1} Pa s (γ_1, η), 10^{-4} m^2 s^{-1} (γ_1/ρ, ν)	ln A_0	E, 10^3 K	T^*_{NI}, K	S or Δn	Refs.	Remarks
1	2	3	4	5	6	7	8	9	10	11
1	4-n-Butoxy-4'-n-pentylazobenzene		*a*	γ_1 (71.6° C)=0.37	—16.45	5.33	359.9		[3]	
2	4,4'-Di-n-alkylazoxybenzenes	 n=4	*b*	γ_1 (25° C)=0.48	—21.8	6.50	304.1	S (294.1 K)= =0.4956 [22]	[9]	see Table 2
3	4,4'-Di-n-alkoxyazoxy benzenes	 n=1 (*p*-azoxyanisole)	*a*	γ_1 (120° C)=0.070	—17.72	5.92	408.5	S (398.5 K) = =0.5784	[23]	see Table 3
4	4-Alkoxy-4'-alkyl-azoxybenzenes	 n=4, m=1 (N=4; BMAOB)	*b*	γ_1 (25° C)=1.89	—14.46	4.55	347.9	S (298.2 K)= =0.7182	[4]	n=5, m=1: T_g=198.7 K [26]
		n=5, m=4		γ_1 (25° C)=1.575			348	[24]	[25]	
		n=4, m=1 (66%), n=2, m=1 (34%)	*a*	γ_1 (40° C)=1.57	—14.01	4.53	376.5		[3]	
				η (20° C)=0.306			346		[27]	
5	4-n-Butyl(4'-alkoxy-benzylidene)-anilines	 n=1 (MBBA)	*b*	γ_1 (25° C)=1.09	—18.92	5.82	318.3	S (308.3 K)= =0.54 [28]	[4]	see Table 4
		n=1 (36%), n=2 (40%), n=4 (24%)		η (20° C)=0.425			336		[27]	
6	(4'-Methoxybenzyl-idene)-4-amino-phenyl acetates	 n=1	*b*	γ_1 (90° C)=0.394	—17.81	6.26	382.20	S(363.09 K)= =0.5954 [28]	[29]	see Table 5
7	4-But-1-enyl(4'-meth-oxybenzylidene)-aniline			η (133° C)=0.30			411.2		[30]	
8	(4'-n-Alkylbenzyl-idene)-4-cyano-anilines	 n=5 (40%), n=7 (60%)		γ_1 (25° C)=3.60, γ_1/η=5.36 at T=0.92 T_{NI}		5.36	343.9		[5]	$E=\partial\gamma_1/\partial\,(T^{-1})$ at T= =0.92 T_{NI}
9	(4'-n-Alkoxybenzyl-idene)-4-cyano-anilines	 n=6 n=8	*a*	γ_1 (60° C)=0.90	—15.05	5.05	373.1		[31]	
				γ_1 (88° C)=1.0			379		[32]	
10	4-Butyl-(4'-methoxy-salicylidene)-aniline		*b*	γ_1 (44° C)=1.33	—22.37	7.349	338.15	S(0.95 T_{NI})= =0.60	[28]	
				γ_1 (T=0.95 T_{NI}) = =0.983						
11	Di-4-methoxybenzyl-ideneazine		*a*	γ_1/ρ(174° C)=0.0444	—10.62	5.44	452		[33]	
12	Di-4-acetoxybenzyl-ideneazine		*a*	γ_1/ρ (174° C)=0.107	—11.97	6.41	465		[33]	
13	4-n-Alkyl-4'-alkyl-tolanes	 n=3, m=4 (50%); n=2, m=5 (50%)							[27]	see compound 14
14	4-Alkoxy-4-n-alkyltolanes	 n=4, m=2(50%); mixture No. 13(50%);		η (20° C)=0.164			320	Δn (25° C)= =0.231	[27]	see Table 6
		n=4, m=2 (30%), n=5, m=1 (40%), n=5, m=2 (30%) n=5, m=4		η (20° C)=0.191			345	Δn (25° C)= =0.297	[27]	
			a	γ_1 (60° C)=0.48	—14.06	4.44	356.6		[3]	
15	4-n-Alkyl-4'-ethoxy-2'-methyltolanes	 n=4 (50%), n=5 (50%)		η (20° C)=[0.329]			321	Δn (20° C)= =0.264	[34]	
16	4-n-Alkyl-4'-ethoxy-2'-fluorotolanes	 n=4 (50%), n=5 (50%)		η (20° C)=[0.244]			331.5	Δn (20° C)= =0.278	[34]	

Table 1 (contd.)

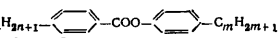
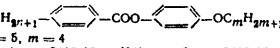
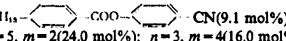
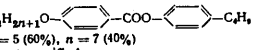
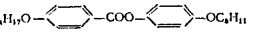
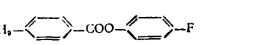
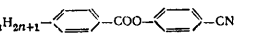
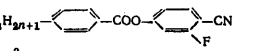
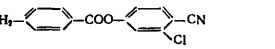
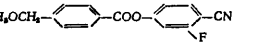
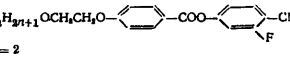
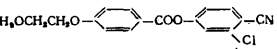
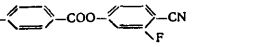
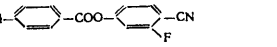
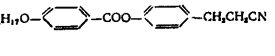
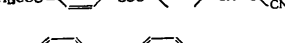
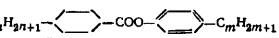
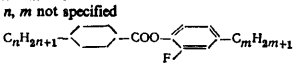
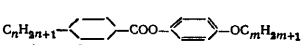
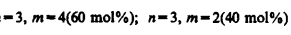
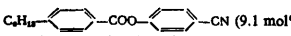
1	2	3	4	5	6	7	8	9	10	11
17	4-n-Alkylphenyl-4-n-alkylbenzoate	 $n=3$, $m=5$		η (20° C)=[0.23] η (25° C)=[0.19]			293		[35] [36]	
		n, m not specified		η (20° C)=0.46, η (0° C)=1.78			332	Δn=0.171	[37]	
18	4-n-Alkoxyphenyl-4-n-alkylbenzoates	 $n=5$, $m=4$	*a*	γ_1 (54.7° C)=0.38	−24.18	7.61			[3]	see Table 7
		$n=4$, $m=2$(45.45 mol%); $n=6$, $m=2$(45.45 mol%);	*b*	γ_1 (25° C)=2.20	−16.7	5.82	320.8	Δn (T= =0.95 T_{NI})= =0.126	[16, 39]	
		 $n=5$, $m=2$(24.0 mol%); $n=3$, $m=4$(16.0 mol%); $n=4$, $m=6$(60.1 mol%)	*a*	η (25° C)=0.38	−14.5	4.05	324.6		[38]	
19	4-Butylphenyl 4-n-alkoxybenzoate	 $n=5$ (60%), $n=7$ (40%)		ν (20° C)=0.85			331		[40]	
		n not specified		η (20° C)=(0.66)			343		[36]	
20	4-n-Pentyloxyphenyl 4-n-octyloxy benzoate			γ_1 (66.3° C)=0.953			357.5	S (339.5 K)= =0.6098 [24]	[7]	$\gamma_1(T)=1.994\cdot 10^3\cdot(1+T/357.65)^{0.2783}\cdot\exp[590.24/(T-214.0)]\sim\sim\rho S^2\exp[B/(T-T_0)]$
21	4-Fluorophenyl 4-butyl-benzoate			η (20° C)=[0.23]			[233]		[41]	
22	4-Cyanophenyl 4-alkylbenzoate	 $n=5$(40 mol%), $n=7$(60 mol%)		γ_1 (25° C)=4.10, $\gamma_1\eta$=5.21 at T=0.92 T_{NI}		6.48	329.4		[5]	$E=\partial\gamma_1/\partial(T^{-1})$ at $T=0,92T_{NI}$ n=7: T_g=214 K [42]; n=2. n=4: T_g=219 K [26]
23	4-Cyano-3-fluoro-phenyl 4-alkyl-benzoate	 $n=3$		η (20° C)=[0.38]			[355]		[43]	$\Delta\varepsilon$=[45.5]
		$n=7$		γ_1 (25° C)=3.3			301.7		[44]	$\Delta\varepsilon$=49.7
24	3-Chloro-4-cyano-phenyl 4-propyl-benzoate			η (20° C)=[1.56]					[45]	$\Delta\varepsilon$=[41]
25	4-Cyano-3-fluoro-phenyl 4-(methoxy-methyl)benzoate			η (20° C)=[0.95]			(300.9)		[45]	$\Delta\varepsilon$=[60]
26	4-Cyano-3-fluoro-phenyl 4-(β-alkoxy-ethoxy)benzoate	 $n=2$		η (20° C)=[0.83]			[281.3]		[43]	$\Delta\varepsilon$=[48.9]
		$n=4$		η (20° C)=[1.08]			[259.9]			$\Delta\varepsilon$=[34.3]
27	3-Chloro-4-cyano-phenyl 4-(β-butoxy-ethoxy)benzoate			η (20° C)=[1.58]			[219.2]		[43]	$\Delta\varepsilon$=[30.8]
28	4-Cyano-3-fluoro-phenyl 4-fluoro-benzoate			η (20° C)=[0.42]			[285.3]		[46]	
29	4-Cyano-3-fluoro-phenyl 4-chloro-benzoate			η (20° C)=[0.68]			[306.3]		[46]	
30	4-(β-Cyanoethyl)-phenyl 4-n-octyl-oxybenzoate			ν (54° C)=0.79			331.2		[47]	
31	4-(Dicyanoethenyl)-phenyl 4-n-heptanoyl-oxybenzoate			ν (80° C)=0.63			375.2		[47]	
32	4-Nitrophenyl 4-n-octyloxybenzoate			γ_1 (69° C)=0.32					[48]	
33	4-Alkylphenyl 4-alkylcyclohexane-1-carboxylates	 $n=m=5$		ν (20° C)=0.13			320		[49]	
		n, m not specified		η (20° C)=(0.18)			313		[36]	
34	4-n-Alkyl-2-fluoro-phenyl 4-alkylcyclo-hexane-1-car-boxylates			η (20° C)=0.22			308		[36]	
35	4-Alkoxyphenyl 4-alkylcyclo-hexane-1-car-boxylates	 $n=4$, $m=2$	*a*	γ_1 (22° C)=1.20	−15.53	4.68	348.7		[50]	see Table 8 n=5, m=1: T_g=197 K [42]
		$n=3$, $m=4$(60 mol%); $n=3$, $m=2$(40 mol%)		γ_1 (25° C)=1.34		4.33	347.3		[5]	$E=\partial\gamma_1/\partial(T^{-1})$ at T= =0.92 T_{NI}
		$n=4$, $m=2$(45.45 mol%); $n=6$, $m=2$(45.45 mol%);	*c*	γ_1 (25° C)=1.34	−6.40	3.45	346.8	Δn (0.95 T_{NI})= =0 073	[16, 39]	
										
		$(n+m)_{av}$=5.88 (in mixture)		η (25° C)=0.16						
		$(n+m)_{av}$=10.00 (in mixture)		η (25° C)=0.51					[51]	
		$n=5$, $m=1$		ν (20° C)=0.17			344		[51]	
		$n=3$, $m=2$		ν (20° C)=0.14			351		[49]	
		$n=4$, $m=2$		ν (20° C)=0.17			348		[49]	
									[49]	

Table 1 (contd.)

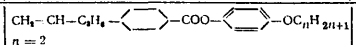
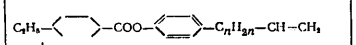
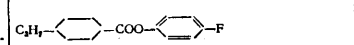
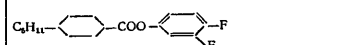
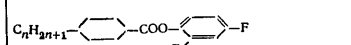
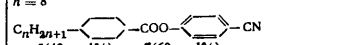
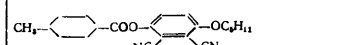
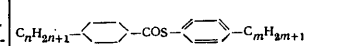
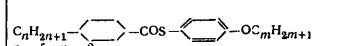
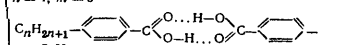
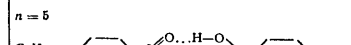
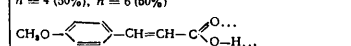
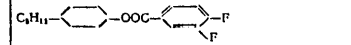
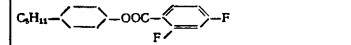
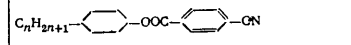
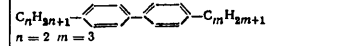
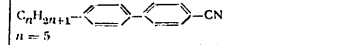
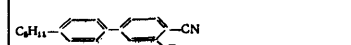
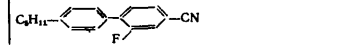
1	2	3	4	5	6	7	8	9	10	11
36	4-Alkoxyphenyl 4-(pent-1-enyl)-cyclohexane-1-carboxylates	 $n=2$ $n=3$	*a* *a*	γ_1 (22° C)=1.20 γ_1 (22° C)=1.08	—17.50 —18.94	5.27 5.67	331.5 318.0	Δn=0.065 Δn=0.061	[48] [48]	
37	4-Alkenylphenyl 4-ethylcyclohexane-1-carboxylates	 $n=1$ $n=2$		η (22° C)=0.225 γ_1 (22° C)=1.25 η (22° C)=0.315			353.2 334.6	Δn=0.062 Δn=0.068	[52] [52]	
38	4-Fluorophenyl 4-propylcyclohexane-1-carboxylate			η (20° C)=0.082					[53]	
39	3,4-Difluorophenyl 4-pentylcyclohexane-1-carboxylate			η (20° C)=[0.194]			(258)		[54]	ΔH_m=3520 K
40	2,4-Difluorophenyl 4-alkylcyclohexane-1-carboxylates	 $n=5$ $n=6$ $n=8$		η (20° C)=[0.17] η (20° C)=[0.22] η (20° C)=[0.22]			(282.0) (284.5) (291.7)		[55]	
41	4-Cyanophenyl 4-alkylcyclohexane-1-carboxylates	 $n=5$(40 mol%), $n=7$(60 mol%)		γ_1 (25° C)=2.69, γ_1/η=6.36 at $T=0.92\,T_{NI}$		4.43	353.4		[5]	$E=\partial\gamma_1/\partial\,(T^{-1})$ at $T=0.92\,T_{NI}$
		$n=5$		ν (50° C)=0.12			352.4		[47]	
42	1-Pentyloxy-2,3-dicyanophenyl 4-methylcyclohexane-1-carboxylate			η (20° C)=[1.5]			(329.4)		[56]	ΔH_m=3830 K
43	4-Alkylphenyl 4-alkylcyclohexane-1-thiolocarboxylate			η (25° C)=(0.37)					[35]	
44	4-Alkoxyphenyl 4-alkylcyclohexane-1-thiolocarboxylate	 $n=5$, $m=2$ $n=4$, $m=5$		η (25° C)=(0.20) η (25° C)=(0.35)					[35] [35]	
45	4-Alkylbenzoic acids	 $n=4$ (50%), $n=6$ (50%)	*b*	γ_1 (72° C)=0.36	—11.9	4.46	381.8	Δn (T=0.95 T_{NI})=0.120	[16, 57]	
		$n=5$	*a*	γ_1 (84° C)=0.53	—8.31	2.74	417.7		[3]	
46	4-Alkylcyclohexane-carboxylic acids	 $n=4$ (50%), $n=6$ (50%)		γ_1 (25° C)=1.85	—3.4	2.97	366.2	Δn (T=0.95 T_{NI})=0.042	[16, 57]	
			c	γ_1 (72° C)=0.33						
47	4-n-Methoxycinnamic acid		*a*	γ_1/ρ(173° C)=0.0956			447		[33]	
48	4-Pentylcyclohexyl 3,4-difluorobenzoate			η (20° C)=[0.70]			(267.2)		[58]	
49	4-Pentylcyclohexyl 2,4-difluorobenzoate			η (20° C)=[0.62]			(289.9)		[58]	
50	4-Alkylcyclohexyl 4-cyanobenzoates			η (25° C)=[0.30]			319.7		[59]	
51	4'-Alkyl-4-n-alkylbiphenyls	 $n=2$ $m=3$ $n=5$ $m=3$ $n=6$ $m=5$		η (20° C)=[0.20] η (20° C)=[0.12] η (20° C)=[0.38]			[284]		[60]	
52	4'-n-Alkyl-4-cyanobiphenyls	 $n=5$ $n=5$(40 mol%), $n=7$(60 mol%)	*b* *a*	γ_1 (25° C)=0.82 γ_1 (25° C)=1.1 γ_1 (25° C)=1.1	—20.0 —17.1	5.84 6.34 5.64	308.2 312.2 312.2	Δn=0.178 Δn (T=307.2 K)=0.185	[16] [61] [16]	see Table 9 T_g=207 K [42]
				γ_1 (25° C)=1.02, γ_1/η=4.35 at $T=0.92\,T_{NI}$		5.58	312.6		[5]	$E=\partial\gamma_1/\partial\,(T^{-1})$ at $T=0.92\,T_{NI}$ $n=2$: T_g=202 K; $n=4$: T_g=206 K [26]
		$n=3$ (30%), $n=5$ (40%), $n=7$ (30%)		η (20° C)=0.34, η (0° C)=1.00			308.2		[62]	
		$n=5$		η (20° C)=[0.34], η (0° C)=[1.38]					[63]	
53	4-Cyano-3-fluoro-4'-n-pentylbiphenyl			η (20° C)=[0.39], η (0° C)=[1.68]			[273.2]		[63]	
54	4-Cyano-2-fluoro-4'-n-pentylbiphenyl			η (20° C)=[0.41], η (0° C)=[2.07]			294.9		[63]	

Table 1 (contd.)

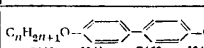
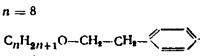
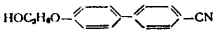
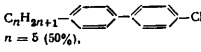
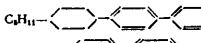
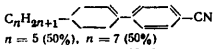
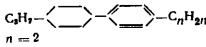
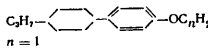
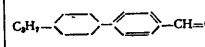
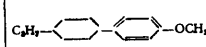
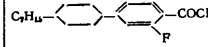
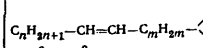
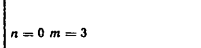
1	2	3	4	5	6	7	8	9	10	11
55	4'-n-Alkoxy-4-cyanobiphenyls	 $n = 5$(40 mol%), $n = 7$(60 mol%)	*b*	γ_1 (31° C) = 2.22	—14.6	5.15	345.2	Δn (T = = 0.95 T_{NI}) = = 0.177	[16]	see Table 10
				γ_1 (25° C) = 3.71, γ_1/η = 3.97 at T = 0.92 T_{NI}		5.71	344.8		[5]	$E = \partial\gamma_1/\partial\,(T^{-1})$ at T = = 0.92 T_{NI}
		$n = 5$	*a*	γ_1 (49.3° C) = 0.56		6.5	341.6		[3]	
				γ_1 (50° C) = 0.27					[64]	$\gamma_1 \simeq -\alpha_2$
				ν (70° C) = 0.18					[65]	
		$n = 8$		γ_1 (76° C) = 0.20			312.2		[64]	$\gamma_1 \simeq -\alpha_2$
56	4'-(β-Alkoxyethyl)-4-cyanobiphenyl	 $n = 1$		η (20° C) = [0.54]			[280.7]		[66]	
		$n = 2$		η (20° C) = [0.57]			[265]		[66]	
57	4-Cyano-4'-(3-hydroxypropoxy)-biphenyl			η (20° C) = [1.5]			386.8		[67]	$\Delta\varepsilon$ = [18.4]
58	4'-Alkyl-4-biphenylyl-acetonitrile	 $n = 5$ (50%),		ν (20° C) = [0.46]			[379]		[68]	
										
59	1-(*p*-Cyanophenyl)-4-n-alkylcyclo-hexenes	 $n = 5$ (50%), $n = 7$ (50%)		η (25° C) = 0.36			332		[69]	
		$n = 2$ (23%), $n = 5$ (38.5%), $n = 7$ (38.5%)		η (25° C) = 0.25			321		[69]	
60	4-Alkyl-1-(4-n-propyl-cyclohexyl)-benzene	 $n = 2$		ν (20° C) = 0.04			(203.2)		[70]	T_g = 159 K [42]
		$n = 3$		η (20° C) = [0.07]			[217]		[71]	$\mu_{\text{ethylbenzene}}$ = 0.37 D
		$n = 5$		η (20° C) = [0.10]			(241)		[34]	
61	4-Alkoxy-1-(4-n-propyl-cyclohexyl)-benzene	 $n = 1$		ν (20° C) = 0.06			(283.2)		[72]	
		$n = 2$		ν (20° C) = 0.07			310.2		[70]	T_g = 191 K [42]
				η (20° C) = [0.135]					[71]	
		$n = 4$		ν (20° C) = 0.10					[49]	$\mu_{\text{ethoxybenzene}}$ = 1.28 D
62	4-(Prop-1-enyl)-1-(4-n-propylcyclo-hexyl)benzene			η (20° C) = [0.17]			358		[71]	$\mu_{\text{propenylbenzene}}$ = 0.71 D
63	4-(4'-Butanoyloxy-phenyl)-4-n-propyl cyclohexane			ν (20° C) = 0.15			303		[49]	$\mu_{\text{phenyl acetate}}$ = 1.52 D
64	1-(3-Hydroxyethoxy)-4-(4-propylcyclo-hexyl)benzene			η (20° C) = [0.91]			354.6		[67]	
65	Methyl *p*-(4-n-propyl-cyclohexyl)-benzoate			η (20° C) = [0.54]			313		[71]	$\mu_{\text{methyl benzoate}}$ = 1.8 D
66	1-(4-n-Alkylcyclo hexyl)-4-fluoro-benzene	 $n = 3$		ν (20° C) = 0.05			(219.2)		[70]	$\mu_{\text{fluorobenzene}}$ = 1.46 D
		$n = 9$		ν (20° C) = [0.034]					[73]	
67	1-(3,4-Difluorophenyl) -4-pentylcyclo-hexane			η (20° C) = [0.07]			[219]		[74]	
68	2-Fluoro-4-(4'-heptyl-cyclohexyl)aceto-phenone			η (20° C) = [0.14]			[271]		[75]	
69	4-Alkyl-1-(4-cyano-phenyl)cyclo-hexane	 $n = 3$		ν (20° C) = 0.20			318.2		[70]	see Tables 11 and 12 T_g = 203 K [26]
		$n = 5$	*c*	γ_1 (25° C) = 0.97	—5.8	2.76	328.2	Δn (T = = 0.95 T_{NI}) = = 0.149	[16]	$\mu_{\text{cyanobenzene}}$ = 4.0 D
70	4-(But-1-enyl)-1-(4-ethoxyphenyl)-cyclohexane			η (22° C) = 0.118			329.7	Δn = 0.085	[52]	
71	4-Alkenyl-1-(4-cyanophenyl)-cyclohexane	$n = 3$ $m = 0$	*a*	γ_1 (22° C) = 1.34	—16.62	4.99	331.7	Δn = 0.116	[76]	see Table 13
		$n = 0$ $m = 5$	*a*	γ_1 (22° C) = 0.99	—14.65	4.32	305.4	Δn = 0.086	[50]	
		$n = 0$ $m = 3$		γ_1 (22° C) = [0.20]		[7.84]	325.7	Δn (T = = 315.7) = = [0.074]		ΔH_m = 3240 K, $K_T = 2.3 \cdot 10^{-12} H$, T = = 315.7 K
72	1-(4-Cyanophenyl)-4-(hepta-4,6-dienyl)-cyclo-hexane			γ_1 (22° C) = [0.16]		[13.90]	[271.7]	Δn (T = = 261.7) = = [0.080]	[50]	ΔH_m = 3370 K, $K_T = 2.5 \cdot 10^{-12} H$, T = = 261.7 K

Table 1 (contd.)

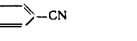
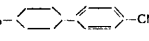
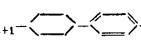
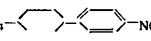
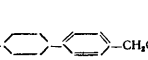
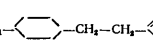
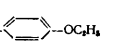
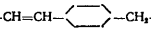
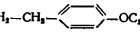
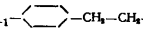
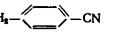
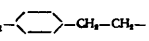
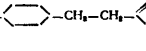
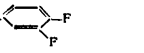
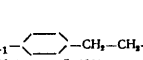
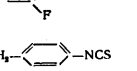
1	2	3	4	5	6	7	8	9	10	
73	4-Alkoxymethyl-1-(4-cyanophenyl)-cyclohexane	$C_nH_{2n+1}OCH_2$––CN $n = 1$ $n = 1$ (50%), $n = 2$ (25%), $n = 6$ (25%)		η (20° C) = [0.34] η (20° C) = [0.14]			302.4 [304]		[77]	there is a difference between the values of η due to the liquid crystal matrix
74	1-(4-Cyanophenyl)-4-(fluoropentyl)-cyclohexane	FC_5H_{10}––CN		γ_1 (22° C) = [0.92]		[7.61]	(307.0)	Δn (T = = 297.0) = = 0.078	[50]	$\Delta H_m = 3180$ K, $K_T = 3.3 \cdot 10^{-12}$ H, T = = 297.0 K
75	4-Alkyl-1-(4-isothiocyanatophenyl)-cyclohexane	C_nH_{2n+1}––NCS $n = 6$	a	η (20° C) = 0.128 γ_1 (22° C) = 0.83, η (22° C) = 0.162	−14.8	4.30	313 317.2	$\Delta n = 0.161$	[34] [78]	$\Delta\varepsilon = 8.9$ $\gamma_1/K_T = 9.1 \cdot 10^{-8}$ s m^{-2} $t_{off} = 41$ ms, $T = 22°$ C
		$n = 3$ (42.9%), $n = 6$ (57.1%) $n = 2$ (44.9%), $n = 6$ (55.1%)		η (20° C) = 0.21 η (20° C) = 0.135 η (20° C) = 0.21					[79] [80] [80]	$\Delta\varepsilon = 7.0$
76	4-Alkenyl-(4-isothiocyanatophenyl)-cyclohexane	C_nH_{2n+1}–CH=CH–C_mH_{2m}––NCS $n = 2$, $m = 2$	a	γ_1 (22° C) = 1.00, η (22° C) = 0.173	−16.33	4.82	310.4		[78]	$\gamma_1/K_T = 9.8 \cdot 10^{-8}$ s m^{-2} $t_{off} = 41$ ms, $T = 22°$ C
				γ_1 (22° C) = 0.97			309.1		[50]	$\gamma_1/K_T = 10.4 \cdot 10^{-8}$ s m^{-2} $T = 22°$ C
		$n = 2$, $m = 0$ (40%); $n = 4$, $m = 0$ (60%) $n = 0$, $m = 2$	a	γ_1 (22° C) = 0.50 γ_1 (22° C) = 0.51		5.40	296.1 316.2		[78] [50]	$\gamma_1/K_T = 5.3 \cdot 10^{-8}$ s m^{-2} $T = 22°$ C
		$n = 0$, $m = 4$		γ_1 (22° C) = 0.95			318.7		[50]	γ_1/K_T (22° C) = = 10.0 $\cdot 10^{-8}$ s m^{-2}
77	4-(4-Pentylcyclohexyl)-phenylacetonitrile	C_5H_{11}––CH_2CN		ν (20° C) = [0.52]			[297]		[68]	
78	2-(4-Ethoxyphenyl)-1-(4-n-pentylcyclohexyl)ethane	C_5H_{11}––CH_2–CH_2––OC_2H_5	a	γ_1 (22° C) = 0.79 η (22° C) = 0.120	−11.61	3.39	319.8	$\Delta n = 0.072$	[52]	
79	2-(4-Ethoxyphenyl)-1-[4-(pent-1-enyl)-cyclohexyl]-ethane	C_3H_7–CH=CH––CH_2–CH_2––OC_2H_5		η (22° C) = 0.118			317.1	$\Delta n = 0.087$	[52]	
80	1-(4-n-Alkylcyclohexyl)-2-(4-cyanophenyl)ethanes	C_nH_{2n+1}––CH_2–CH_2––CN $n = 5$	a	γ_1 (22° C) = 1.80, η (22° C) = 0.221		4.87	325.7		[76]	$\gamma_1/K_T = 1.22 \cdot 10^{-10}$ s m^{-2} $t_{off} = 43$ ms, $T = 22°$ C
		$n = 3$	a	η (20° C) = (0.195), η (0° C) = (0.44)		3.27	317.7		[81]	
		$n = 3$ (30%), $n = 5$ (40%), $n = 7$ (30%)		η (20° C) = 0.25, η (0° C) = 0.86			322.2		[65]	
81	1-(4-n-Alkenylcyclohexyl)-2-(4'-cyanophenyl)-ethanes	C_nH_{2n+1}–CH=CH–C_mH_{2m}––CH_2–CH_2––CN $n = 3$, $m = 0$	a	γ_1 (22° C) = 1.70, η (22° C) = 0.228	−15.60	4.76	319.9	Δn (T = = 309.9) = = 0.118	[76]	$\gamma_1/K_T = 1.21 \cdot 10^{-10}$ s m^{-2} $t_{off} = 38$ ms, $T = 22°$ C
		$n = 1$, $m = 0$ (60%); $n = 0$, $m = 2$ (40%)		γ_1 (22° C) = 2.15	−16.15	4.99	329.9	Δn (T = = 319.9) = = 0.122	[76]	$\gamma_1/K_T = 1.11 \cdot 10^{-10}$ s m^{-2} $t_{off} = 29$ ms, $T = 22°$ C
		$n = 0$, $m = 2$ (40%), CH_3–CH=CH–C_6H_4––CN (60%)		γ_1 (22° C) = 1.80			333.5	Δn (T = = 323.5) = = 0.125	[76]	$\gamma_1/K_T = 0.92 \cdot 10^{-10}$ s m^{-2} $t_{off} = 27$ ms, $T = 22°$ C
82	1-(3,4-Difluorophenyl)-2-(4-propylcyclohexyl)ethane	C_3H_7––CH_2–CH_2–(F, F)		η (20° C) < [0.08]			[280.7]		[53]	
83	1-(4-Cyano-3-fluorophenyl)-2-(4-propylcyclohexyl)-ethane	C_3H_7––CH_2–CH_2–(CN, F)		η (20° C) = [0.251]			(280.1)		[53]	$\Delta H_m = 1970$ K, $\Delta\varepsilon = 18.9$
84	1-(4-n-Alkylcyclohexyl)-2-(4-isothiocyanotophenyl)-ethanes	C_nH_{2n+1}––CH_2–CH_2––NCS $n = 3$ (10%), $n = 5$ (60%)	a	γ_1 (22° C) = 1.05, η (22° C) = 0.115		4.82	317.6	$\Delta n = 0.115$	[78]	$\gamma_1/K_T = 6.9 \cdot 10^{-8}$ s m^{-2} $t_{off} = 21$ ms, $T = 22°$ C
85	β-(4-Chlorophenyl)-ethyl 4-heptylcyclohexane-1-carboxylate	C_7H_{15}––COO–CH_2CH_2––Cl		η (20° C) = [0.11]			(241)		[82]	

Table 1 (contd.)

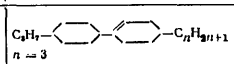
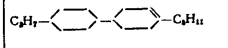
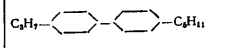
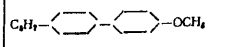
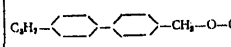
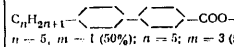
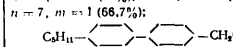
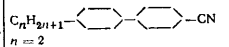
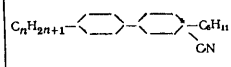
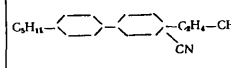
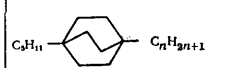
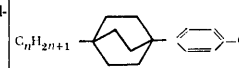
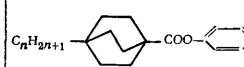
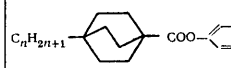
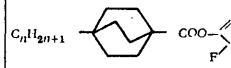
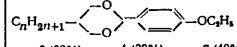
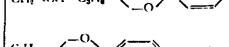
1	2	3	4	5	6	7	8	9	10	11
86	4-Alkyl-1-(4-propylcyclohexyl)cyclohex-1-ene									
		$n = 3$		η (20° C) = [0.054]			285		[34]	
		$n = 5$		η (20° C) = [0.079]			300			
		$n = 7$		η (20° C) = [0.093]			312			
87	4-Pentyl-1-(4-propylcyclohexyl)cyclohex-3-ene			η (20° C) = [0.079]			295		[34]	
88	4-Pentyl-1-(4-propylcyclohexyl)-cyclohexane			η (20° C) = [0.065]			370		[34]	
89	4-Methoxy-1-(4-n-propylcyclohexyl)cyclohexane			ν (20° C) = (0.07)			290		[72]	
90	1-(4-Methoxymethylcyclohexyl)-4-propylcyclohexane			η (20° C) = [0.05]			324.2		[83]	
91	Alkyl 4-(4-n-alkylcyclohexyl)-cyclohexane-1-carboxylate									
		$n = 5$, $m = 1$ (50%); $n = 5$; $m = 3$ (50%)		η (20° C) = [0.14]			351		[84]	
		$n = 7$, $m = 1$ (66.7%);		η (20° C) = [0.07]			351		[84]	
										
92	4-*e*-(4-Alkylcyclohexyl)-1-*e*-cyanocyclohexane									
		$n = 2$		ν (20° C) = [0.65]			322		[49]	
		$n = 3$		ν (20° C) = [0.63]			353		[49, 40]	
		$n = 4$		ν (20° C) = [0.68]			352		[49]	
		$n = 5$		ν (20° C) = [0.65]			358		[49]	
		$n = 7$		ν (20° C) = [0.75]			355		[49]	
93	4-*e*-(4-Alkylcyclohexyl)-1-*a*-cyano-1-*e*-pentylcyclohexane			η (20° C) = 0.70			338		[40]	
94	1-*e*-(But-2-enyl)-1-*a*-cyano-4-*e*-(4-pentylcyclohexyl)-cyclohexane			γ_1 (22° C) = [1.58]		[6.62]	[325.8]		[52]	
				η (22° C) = [0.50]						
95	1-Alkyl-4-pentylbicyclo[2.2.2]-octane									
		$n = 5$		η (20° C) = [0.077], η (0°) = [0.202]			[237]		[85]	
		$n = 7$		η (20° C) = [0.084], η (0°) = [0.222]			[243]		[85]	
96	1-Alkyl-4-cyanophenylbicyclo[2.2.2]-octanes									
		$n = 5$	*a*	γ_1 (60° C) = 0.48	−14.2	4,48	374.4	Δn ($T = 0.95T_{NI}$) = = 0.118	[3]	
		n = 3(40 mol%), n = 5(60 mol%)	*c*	γ_1 (25° C) = 2.96 γ_1 ($T = 0.95T_{NI}$) = = 0.21	−11.3	3,60	369.7		[16]	a more accurate fitting formula is $\ln[\gamma_1/(\Delta n)^2] = -6.40 + 0.743/(T - 198.8)$
		n = 5(40 mol%), n = 7(60 mol%)	*a*	γ_1 (25° C) = (3.6)		4,94	367.7		[61]	
		n = 3 (30%), n = 5 (40%), n = 7 (30%)		η (20° C) = 0.96			363.2		[62]	
97	4-Alkylphenyl 4-alkylbicyclo[2.2.2]-octane-1-carboxylates		*a*	η (20° C) = (0.34)		1,73 T = 20° C	333		[36]	
98	4-Alkoxyphenyl 4-alkylbicyclo[2.2.2]-octane-1-carboxylates		*a*	η (20° C) = (0.64)		1,33 T = 20° C	368		[36]	
99	4-Alkyl-2-fluorophenyl 4-alkylbicyclo[2.2.2]-octane-1-carboxylates		*a*	η (20° C) = (0.44)		2,08 T = 20° C	333		[36]	
100	5-Alkyl-2-(4-ethoxyphenyl)-1,3-dioxanes									
		n = 3 (30%), n = 4 (30%), n = 7 (40%)		η (20° C) = 0.287			318		[27]	
101	2-(4-Butoxyphenyl)-5-(pent-1-en-3-yl)-1,3-dioxane		*a*	γ_1 (22° C) = [0.70]		[8.52]	308.4		[52]	
102	2-(4-Alkenyloxyphenyl)-5-pentyl-1,3-dioxanes									
		$n = 1$	*a*	γ_1 (22° C) = [1.30]		[7.66]	295.2		[52]	
		$n = 2$		γ_1 (22° C) = 1.18			274.1		[52]	

Table 1 (contd.)

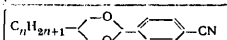
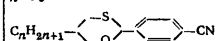
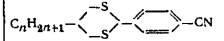
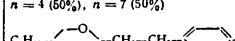
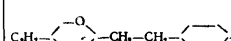
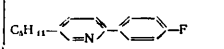
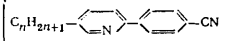
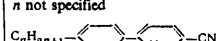
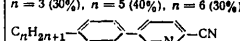
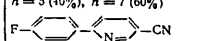
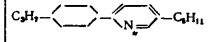
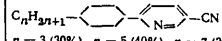
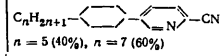
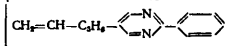
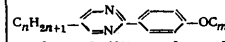
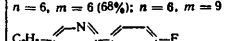
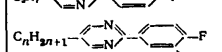
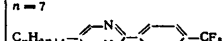
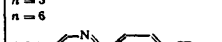
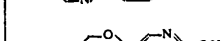
1	2	3	4	5	6	7	8	9	10	11
103	5-Alkyl-2-(4-cyanophenyl)-1,3-dioxanes									
		n = 5(40 mol%), n = 7(60 mol%)		γ_1 (25° C) = 1.34, γ_1/η = 5.59 at $T = 0.92T_{NI}$		3.10	323.0		[5]	$E = \partial\gamma_1/\partial(T^{-1})$ at $T = 0.92T_{NI}$
		n = 3 (30%), n = 5 (40%), n = 7 (30%)		η (20° C) = 0.41, η (0° C) = 1.48			318.2		[62]	
		n = 5		η (20° C) = [0.46]			(325)		[86]	
104	5-Alkyl-2-(4-cyanophenyl)-1,3-oxathianes									
		n = 4 (50%), n = 7 (50%)		η (20° C) = [0.54]			(288), n = 7		[87]	ΔH_m = 3650 K
105	5-Alkyl-2-(4-cyanophenyl)-1,3-dithiane									
		n = 4 (50%), n = 7 (50%)		η (20° C) = [0.74]					[88]	
106	5-Alkyl-2-[2-(4-cyanophenyl)ethyl]-1,3-dioxane			η (20° C) = [0.55]			(292)		[86]	
107	5-Propyl-2-[2-(4-propylcyclohexyl)ethyl]-1,3-dioxane			η (20° C) = [0.27]				Δn = 0.033	[89]	
108	5-(4-Fluorophenyl)-5-pentylpyridine			η (20° C) = [0.126]			[228.5]		[90]	
109	5-Alkyl-2-(4-cyanophenyl)pyridines									
		n = 5	b	γ_1 (25° C) = 1.28, γ_1 (T = = 0.95T_{NI}) = 1.03	—11.6	3.50	316.7	Δn (T = = 0.95T_{NI}) = = 0.176	[91]	
		n = 6	b	γ_1 (25° C) = 0.98, γ_1 (T = = 0.95T_{NI}) = 2.34	—18.9	5.75	305.7	Δn (T = = 0.95T_{NI}) = = 0.163	[91]	
		n = 7	b	γ_1 (25° C) = 2.15, γ_1 (T = = 0.95T_{NI}) = 1.47	—14.7	4.60	320.2	Δn (T = = 0.95T_{NI}) = = 6.272	[91]	
		n = 5(40 mol%), n = 7(60 mol%)	b	γ_1 (25° C) = 1.84	—16.0	5.40	317.4	Δn (T = = 0.95T_{NI}) = = 0.175	[16]	
		n not specified	a	γ_1 (25° C) = 1.46		6.38	317.4		[61]	
				η (20° C) = 0.496			314	Δn = 0.211	[34]	$\Delta\varepsilon$ = 22.9
110	2-(4-Alkylphenyl)-5-cyanopyridines									
		n = 3 (30%), n = 5 (40%), n = 6 (30%)	a	γ_1 (25° C) = 3.50		5.86	335.9		[92]	$\Delta\varepsilon$ = 7.3
111	5-(4-Alkylphenyl)-2-cyanopyridines									
		n = 5 (40%), n = 7 (60%)	a	γ_1 (25° C) = 2.20		5.74	322.4		[92]	$\Delta\varepsilon$ = 11.3
112	5-Cyano-2-(4-fluorophenyl)pyridine			η (20° C) = [0.25]			[313]		[90]	
113	5-n-Pentyl-2-(4-n-propylcyclohexyl)pyridine			η (20° C) = [0.104]			180		[90]	
114	2-(4-Alkylcyclohexyl)-5-cyanopyridines									
		n = 3 (30%), n = 5 (40%), n = 7 (30%)	a	γ_1 (25° C) = 1.40		5.63	330.5		[92]	$\Delta\varepsilon$ = 3.3
115	5-(4-Alkylcyclohexyl)-2-cyanopyridines									
		n = 5 (40%), n = 7 (60%)	a	γ_1 (25° C) = 1.78		5.57	331.2		[92]	$\Delta\varepsilon$ = 12.4
116	5-(Pent-4-enyl)-2-(4-pentylphenyl)-pyrimidine			η (22° C) = [0.30]			[243.8]		[52]	
117	5-Alkyl-2-(4-alkoxyphenyl)-pyrimidines									
		n = 5, m = 8 (60%); n = 3, m = 8 (40%)		η (20° C) = 0.40			338		[40]	
		n = 6, m = 6 (68%); n = 6, m = 9 (32%)		η (20° C) = 0.688			333		[27]	
118	2-(4-Fluorophenyl)-5-propylpyrimidine			η (20° C) = [0.087]			325.9		[93]	
119	5-Alkyl-2-(3,4-difluorophenyl)-pyrimidines								[94]	
		n = 2		η (20° C) = [0.138]						
		n = 3		η (20° C) = [0.158]						
		n = 4		η (20° C) = [0.174]						
		n = 5		η (20° C) = [0.185]						
		n = 6		η (20° C) = [0.196]						
		n = 7		η (20° C) = [0.301]						
120	5-Alkyl-2-(4-trifluoromethylphenyl)-pyrimidine								[95]	
		n = 2		η (20° C) = [0.11]				Δn = [0.07]		$\Delta\varepsilon$ = [37]
		n = 3		η (20° C) = [0.15]				Δn = [0.08]		$\Delta\varepsilon$ = [40]
		n = 4		η (20° C) = [0.24]			(305)	Δn = [0.07]		$\Delta\varepsilon$ = [31]
		n = 5		η (20° C) = [0.24]			(314)	Δn = [0.08]		$\Delta\varepsilon$ = [36]
		n = 6		η (20° C) = [0.29]			(303)	Δn = [0.07]		$\Delta\varepsilon$ = [25]
121	5-Methoxy-2-(4-trifluoromethylphenyl)pyrimidine			η (20° C) = [0.41]				Δn = [0.06]	[95]	$\Delta\varepsilon$ = [35]
122	5-n-Alkyl-2-(2-n-pentyl-5-pyrimidinyl)-1,3-dioxanes									
		n = 3		η (20° C) = [0.13]			(338)	Δn = [0.03]	[96]	$\Delta\varepsilon$ = [13]
		n = 5		η (20° C) = [0.13]			370	Δn = [0.03]	[96]	$\Delta\varepsilon$ = [8]

Table 1 (contd.)

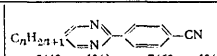
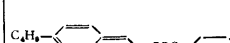
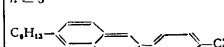
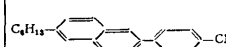
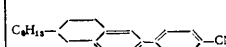
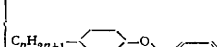
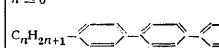
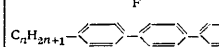
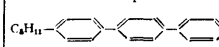
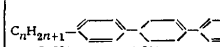
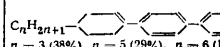
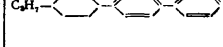
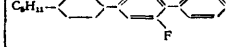
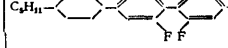
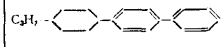
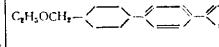
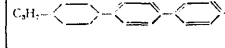
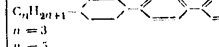
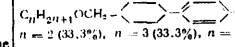
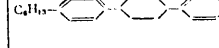
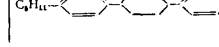
1	2	3	4	5	6	7	8	9	10	11
123	5-Alkyl-2-(4-cyanophenyl)-pyrimidines									
		$n = 5$(40 mol%), $n = 7$(60 mol%)	*b*	γ_1 (25° C) = 1.91	−14.9	5.11	324.4	Δn (T = =0.95T_{NI})= = 0.177	[16]	T_g = 215 K [42]
			b	γ_1 (25° C) = 2.01		5.64	324.2		[5]	$E = \partial\gamma_1/\partial\,(T^{-1})$ at T= =0.92 T_{NI}
		$n = 7$		η (25° C) = [0.50]			(324)		[86]	$n = 5$: T_g = = 214 K [26],
		n not specified		η (20° C) = 0.528			319	Δn = 0.195	[34]	$\Delta\varepsilon$ = 23.6
124	2-[2-(4-Cyanophenyl)-ethyl]-5-pentyl-pyrimidine			η (20° C) = [0.56]			[262]		[86]	
125	4-n-Alkylcyclo-hexyl 6-n-butyl-2-naph-thoates									
		$n = 3$	*a*	η (25° C) = (1.60)	−15.67	4.81	349.2		[97]	
		$n = 4$	*a*	η (25° C) = (1.85)	−15.73	4.87	342.2			
		$n = 5$	*a*	η (25° C) = (1.80)	−15.96	4.93	350.2			
126	2-(4-Cyanophenyl)-6-n-hexylnaph-thalene		*a*	η (20° C) = (1.76), η (70° C) = 0.15, η (80° C) = 0.11		2.05	390.2		[98]	
127	2-(4-Cyanophenyl)-6-n-hexyl-5,6-dihy-dronaphthalene		*a*	η (20° C) = (4.10), η (70° C) = 0.285		2.24	352.9		[98]	
128	2-(4-Cyanophenyl)-6-n-hexyl-5,6,7,8-tetrahydro-naphthalene		*a*	η (80° C) = 0.166			375.6		[98]	
129	6-Alkyl-2-hexyl-phenyl-*trans*-1,3-dioxadecalins									
		$n = 5$		η (20° C) = [1.26]			367.2		[99]	ΔH_m = 4909 K
		$n = 6$		η (20° C) = [1.27]			361.3			ΔH_m = 3983 K
130	4'-Alkyl-1-(4-alkyl-phenyl)-2-fluoro-biphenyl			η (20° C) = [0.40], η (0° C) = [1.15]			414		[100]	
131	4'-Alkoxy-1-(4-alkyl-phenyl)-2-fluoro-biphenyl			η (20° C) = [0.75], η (0° C) = [3.00]			453		[100]	
132	4-Cyano-4''-pentyl-terphenyl			η (20° C) = [0.82]			[546]		[101]	
133	1-[4-(4-Alkylphenyl)-cyclohex-1-enyl]-4-fluoro-benzene						(347)		[102]	
		$n = 3$ (50%), $n = 4$ (50%)		η (20° C) = [0.16]			[317]			
134	4-n-Alkyl-1-(4'-cyano-4-biphenylyl)-cyclohexenes									
		$n = 3$ (38%), $n = 5$ (29%), $n = 6$ (16%), $n = 7$ (12%)		η (25° C) = 0.35			333		[68]	
		$n = 3$ (45%), $n = 5$ (34%), $n = 7$ (16%), $n = 6$ (5.3%)		η (25° C) = 0.35			334		[68]	
135	4-Ethyl-4'-(4-n-propyl-cyclohexyl)-biphenyl			ν (20° C) = (0.20)			437.2		[70]	
				η (20° C) = (0.336)			438		[27]	
136	4-Ethyl-2'-fluoro-4'-(4-pentylcyclo-hexyl)biphenyl			ν (20° C) = (0.27)			380.2		[70]	
137	4-Ethyl-2,2'-difluoro-4'-(4-pentyl-cyclohexyl)-biphenyl			ν (20° C) = (0.42)			315.2		[70]	
138	4-Methoxy-4'-(4-n-propylcyclo-hexyl)biphenyl			ν (20° C) = (0.70)			438.2		[70]	
139	4-Ethoxymethyl-1-(4'-methyl-4-bi-phenylyl)cyclohexane			η (20° C) = (0.43)			412.7		[103]	
140	4-Fluoro-4'-(4-n-propylcyclo-hexyl)biphenyl			ν (20° C) = (0.24)			426.2		[70]	
141	4'-(4-n-Alkylcyclo-hexyl)-4-cyano-biphenyl									
		$n = 3$		ν (20° C) = (0.90)			495.2		[70]	
		$n = 5$		η (20° C) = [1.08]			[563]		[104]	
142	4-Alkoxymethyl-1-(4'-cyano-4-bi-phenylyl)cyclohexane									
		$n = 2$ (33.3%), $n = 3$ (33.3%), $n = 5$ (33.3%)		η (20° C) = [0.55]			453		[76]	
143	1-(4-Fluorophenyl)-4-(4-hexylphenyl)-cyclohexane			η (20° C) = [0.19]			[316]		[102]	
144	1-(4-Cyanophenyl)-4-(4-pentylphenyl)-cyclohexane			η (20° C) = [0.48]			[474]		[104]	

Table 1 (contd.)

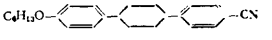
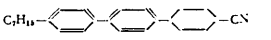
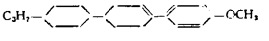
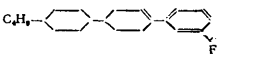
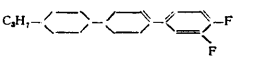
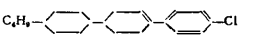
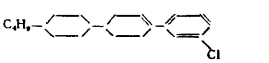
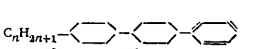
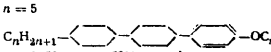
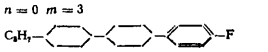
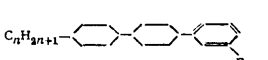
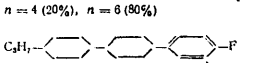
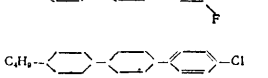
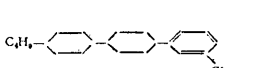
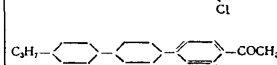
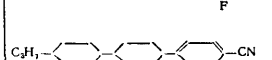
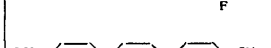
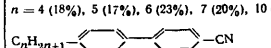
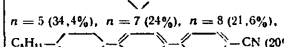
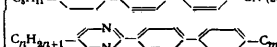
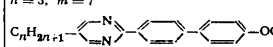
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145	1-(4-Cyanophenyl)-4-(4-hexyloxyphenyl)cyclohexane			η (20° C) = [0.25]			[477]		[104]	
146	4-(4-Cyanocyclohexyl)-4′-n-heptylbiphenyl			η (20° C) = [0.26]			[522]		[104]	
147	1-[4-(4-Propylcyclohexyl)cyclohex-1-enyl]-4-methoxybenzene			η (20° C) = [0.23]			475.4		[105]	
148	1-[4-(4-Butylcyclohexyl)cyclohex-1-enyl]-3-fluorobenzene			η (20° C) = [0.23]			364		[102]	
149	1,2-Difluoro-4-[4-(4-propylcyclohexyl)cyclohex-1-enyl]benzene			η (20° C) = [0.27]			388.2		[102]	
150	1-[4-(4-Butylcyclohexyl)cyclohex-1-enyl]-4-chlorobenzene			η (20° C) = [0.29]			456.6		[102]	
151	1-[4-(4-Butylcyclohexyl)cyclohex-1-enyl]-3-chlorobenzene			η (20° C) = [0.47]			340.7		[102]	
152	[4-(4-Alkylcyclohexyl)cyclohexyl]-benzene	 $n = 5$ (50%), $n = 7$ (50%) $n = 5$		η (20° C) = [0.23] η (20° C) = [0.23]			379.3 385.0		[105] [105]	
153	4-Alkoxy-1-[4-(4-alkylcyclohexyl)cyclohexyl]-benzene	 $n = 3$ (50%), n 6 (50%) $m = 1$ $n = 0$ $m = 1$ $n = 0$ $m = 3$		η (20° C) = [0.23] η (20° C) = [0.30] η (20° C) = [0.38]			479		[105] [105] [105]	
154	4-Fluoro-1-[4-(4-propylcyclohexyl)cyclohexyl]-benzene			η (20° C) = [0.11]			431.7		[102]	
155	1-[4′-(4-Alkylcyclohexyl)cyclohexyl]-3-fluorobenzene	 $n = 4$ (20%), $n = 6$ (80%)		η (20° C) = [0.23]			360.8		[102]	
156	1,2-Difluoro-4-[4-(4-propylcyclohexyl)cyclohexyl]-benzene			η (20° C) = [0.23] η (20° C) = [0.21]			397.3 391		[102] [53]	
157	1-[4-(4-Butylcyclohexyl)cyclohexyl]-4-chlorobenzene			η (20° C) = [0.30]			455.2		[102]	
158	1-[4-(4-Butylcyclohexyl)cyclohexyl]-3-chlorobenzene			η (20° C) = [0.69]			313		[102]	
159	2-Fluoro-4-[4-(4-propylcyclohexyl)cyclohexyl]-acetophenone			η (20° C) = [0.36]					[74]	
160	4-Cyano-3-fluoro-1-[4-(4-propylcyclohexyl)cyclohexyl]-benzene			η (20° C) = [0.547] η (20° C) = [0.44]			480.8		[53] [74]	
161	4-Cyano-4″-propyl-*p*-tercyclohexyl			η (20° C) = [1.00]			[488]		[106]	
162	7α-Alkyl-2β-hexanoyloxyperhydrophenanthrenes	 $n = 4$ (18%), 5 (17%), 6 (23%), 7 (20%), 10 (22%)		ν (20° C) = 0.41			348	$\Delta n = 0.05$	[107]	$\Delta\varepsilon = -0.5$
163	2-Alkyl-7-cyanofluorene	 $n = 5$ (34.4%), $n = 7$ (24%), $n = 8$ (21.6%),  (20%)		ν (20° C) = 3.25			335—340	$\Delta n = 0.208$	[108]	
164	5-Alkyl-2-(4′-alkyl-4-biphenylyl)-pyrimidines	 $n = 5$, $m = 2$ $n = 6$, $m = 2$ $n = 2$, $m = 3$ $n = 5$, $m = 5$ $n = 3$, $m = 7$		η (20° C) = [0.32] η (20° C) = [0.27] η (20° C) = [0.28] η (20° C) = [0.35] η (20° C) = [0.29]			440 428 452 446 441	$\Delta n = [0.27]$ $\Delta n = [0.30]$ $\Delta n = [0.30]$	[101]	$\Delta\varepsilon = [9.2]$ $\Delta\varepsilon = [7.9]$ $\Delta\varepsilon = [11.2]$
165	5-Alkyl-2-(4′-propoxy-4-biphenylyl)-pyrimidines	 $n = 2$ $n = 6$ $n = 7$		η (20° C) = [0.56] η (20° C) = [0.54] η (20° C) = [0.47]			478 462 464		[101]	

Table 1 (contd.)

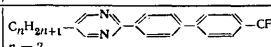
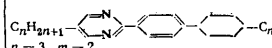
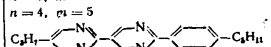
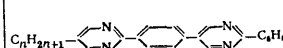
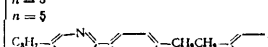
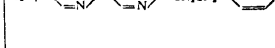
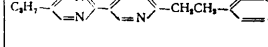
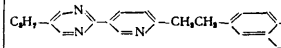
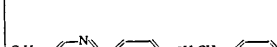
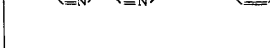
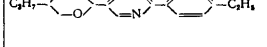
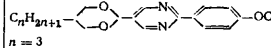
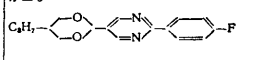
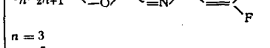
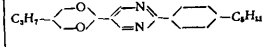
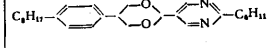
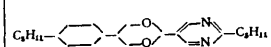
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166	5-Alkyl-2-[4′-trifluoromethyl-4-biphenylyl]-pyrimidines								[95]	
		$n = 2$		η (20° C) = [0.33]			527	Δn = [0.20]		$\Delta\varepsilon$ = [43]
		$n = 3$		η (20° C) = [0.38]			513	Δn = [0.22]		$\Delta\varepsilon$ = [41]
		$n = 4$		η (20° C) = [0.43]			503	Δn = [0.19]		$\Delta\varepsilon$ = [32]
		$n = 5$		η (20° C) = [0.40]			501	Δn = [0.20]		$\Delta\varepsilon$ = [34]
		$n = 6$		η (20° C) = [0.52]			495	Δn = [0.19]		$\Delta\varepsilon$ = [29]
167	5-Alkyl-2-[4-(4-alkylcyclohexyl)-phenyl]-pyrimidines								[101]	
		$n = 3$, $m = 2$		η (20° C) = [0.30]			446	Δn = [0.19]		$\Delta\varepsilon$ = [6.5]
		$n = 4$, $m = 2$		η (20° C) = [0.48]			426			
		$n = 5$, $m = 2$		η (20° C) = [0.26]			435			
		$n = 2$, $m = 3$		η (20° C) = [0.27]			457	Δn = [0.21]		$\Delta\varepsilon$ = [6.5]
		$n = 6$, $m = 3$		η (20° C) = [0.41]			443			
		$n = 5$, $m = 4$		η (20° C) = [0.30]			446			
		$n = 4$, $m = 5$		η (20° C) = [0.33]			448			
168	2(n-Pentylphenyl)-5′-propyl-5,2′-bipyrimidine			η (20° C) = [0.57]			[488]	Δn = [0.30]	[109]	$\Delta\varepsilon$ = [32]
169	5-Alkyl-2-[4-(2-pentyl-5-pyrimidinyl)-phenyl]-pyrimidine								[110]	
		$n = 3$		η (20° C) = [1.16]			[546]		[110]	
		$n = 5$		η (20° C) = [3.0]			[546]	Δn = [0.27]	[110]	$\Delta\varepsilon$ = [27]
170	2-[β-(4-Ethylphenyl)-ethyl]-5-(5-propyl-2-pyrimidinyl)-pyridine			η (20° C) = [0.24]			[371]	Δn = [0.20]	[111]	$\Delta\varepsilon$ = [16]
171	2-[β-(4-Methoxyphenyl)ethyl]-5-(5-propyl-2-pyrimidinyl)pyridine			η (20° C) = [0.31]			[423]	Δn = [0.25]	[111]	$\Delta\varepsilon$ = [20]
172	2-[β-(4-Fluorophenyl)-ethyl]-5-(5-propyl-2-pyrimidinyl)-pyridine			η (20° C) = [0.38]			[355]	Δn = [0.19]	[111]	$\Delta\varepsilon$ = [46]
173	2-[β-(3,4-Difluorophenyl)ethyl]-5-(5-propyl-2-pyrimidinyl)-pyridine			η (20° C) = [0.48]			[333]	Δn = [0.19]	[111]	$\Delta\varepsilon$ = [34]
174	2-[β-(4-Cyanophenyl)-ethyl]-5-(5-pentyl-2-pyrimidinyl)-pyridine			η (20° C) = [1.23]			[449]	Δn = [0.33]	[111]	$\Delta\varepsilon$ = [61]
175	2-[2-(4-Ethylphenyl)-5-pyrimidinyl]-5-n-propyl-1,3-dioxane			η (20° C) = [0.30]			458	Δn = [0.20]	[95]	$\Delta\varepsilon$ = [15]
176	5-n-Alkyl-2-[2-(4-butoxyphenyl)-5-pyrimidinyl]-1,3-dioxane									
		$n = 3$		η (20° C) = [0.34]			491	Δn = [0.19]	[95]	$\Delta\varepsilon$ = [21]
		$n = 6$		η (20° C) = [0.33]			476	Δn = [0.16]	[95]	$\Delta\varepsilon$ = [17]
177	2-[2-(4-Fluorophenyl)-5-pyrimidinyl]-5-n-propyl-1,3-dioxane			η (20° C) = [0.20]			446	Δn = [0.12]	[95]	$\Delta\varepsilon$ = [23]
178	5-n-Alkyl-2-[2-(3,4-difluorophenyl)-5-pyrimidinyl]-1,3-dioxane									
		$n = 3$		η (20° C) = [0.38]			425	Δn = [0.23]	[95]	$\Delta\varepsilon$ = [28]
		$n = 5$		η (20° C) = [0.40]			419	Δn = [0.22]	[95]	$\Delta\varepsilon$ = [26]
179	2-[2-(4-Pentylcyclohexyl)-5-pyrimidinyl]-5-n-propyl-1,3-dioxane			η (20° C) = [0.27]			438	Δn = [0.12]	[95]	$\Delta\varepsilon$ = [21]
180	5-(4-n-Octylphenyl)-2-(2-pentyl-5-pyrimidinyl)-1,3-dioxane			η (20° C) = [0.43]			429	Δn = [0.10]	[95]	$\Delta\varepsilon$ = [16]
181	5-(4-n-Pentylcyclohexyl)-2-(2-pentyl-5-pyrimidinyl)-1,3-dioxane			η (20° C) = [0.28]			390	Δn = [0.08]	[95]	$\Delta\varepsilon$ = [18]
182	5-(1-Butyl-4-piperidinyl)-2-(4-cyanophenyl)-1,3-dioxane			η (25° C) = (1.54)			442		[112]	$\Delta\varepsilon$ (82° C) = = +12
183	1-[5-(n-Alkylphenyl)-2-pyrimidinyl]-4-cyanocyclohexane									
		$n = 5$ (40%), $n = 7$ (60%)	*a*	η (60° C) = 0.840		[4.50]	438		[113]	T_m = 336 K, $\Delta\varepsilon$ (60° C) = = 19.80

Table 1 (contd.)

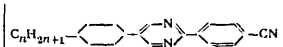
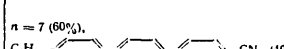
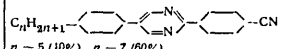
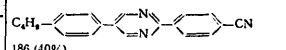
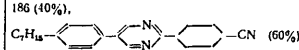
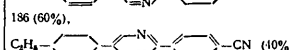
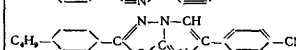
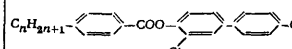
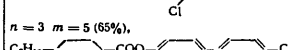
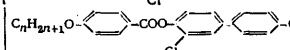
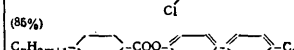
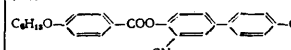
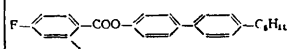
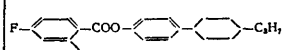
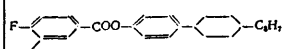
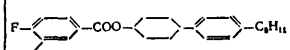
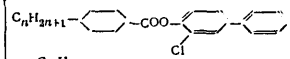
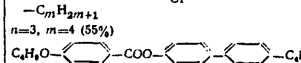
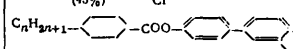
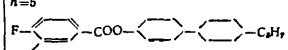
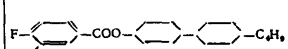
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184	4-[5-(4-n-Alkylcyclohexyl)-2-pyrimidinyl]-benzonitrile	 $n = 5$ (10%), $n = 7$ (60%)	*a*	η (60° C) = 0.306		[3.45]	495		[113]	T_m = 340 K, Δε (60° C) = = 17.20
		$n = 7$ (60%),  (10%)	*a*	η (60° C) = 0.286			492		[113]	T_m = 317 K, Δε (60° C) = = 15.26
185	4-[5-(4-n-Alkylcyclohexyl)-2-pyrimidinyl]-cyclohexane-carbonitrile	 $n = 5$ (10%), $n = 7$ (60%)	*a*	η (60° C) = 0.385		[3.81]	471		[113]	T_m = 330 K, Δε (60° C) = = 16.30
186	4-[5-(4-n-Butylphenyl)-2-pyrimidinyl]-benzonirtrile	 186 (40%),  (60%)	*a*	η (60° C) = 0.385		[1.39]	501		[113]	T_m = 359 K, Δε (60° C) = = 19.20
		186 (60%),  (10%)	*a*	η (60° C) = 0.550			509		[113]	T_m = 343 K, Δε (60° C) = = 22.90
187	2-(4-Butylcyclohexyl)-6-(4-cyanophenyl)-imidazo-[2,1-*b*]-1,3,4-thia-diazole			γ_1 (25° C) = [5.6]		[10.0]	>551 (decom-poses)		[114]	T_m = 445 K
				γ_1 (60° C) = [0.46]						
188	4-(4-Alkylphenyl)-2-chloro-phenyl 4-alkyl-benzoates									
		$n = 3$ $m = 5$ (65%),  (35%)		η (50° C) = 0.30			398		[115]	
189	4-(4-Alkylphenyl)-2-chloro-phenyl 4-alkoxy-benzoates			η (50° C) = 0.65			373		[115]	
		(85%)  (15%)								
190	4-(4-n-Butyl-phenyl)-2-cyanophenyl 4-(4-n-hexyloxyl)-benzoate			η (20° C) = [4.6]			[407]		[116]	Δε = [−4.3]
191	4'-Pentyl-4-biphenylyl 2,4-difluoro-benzoate			η (20° C) = [0.42]			429.9		[117]	Δε = [+2.7]
192	4-(4-Propyl-cyclo-hexyl)phenyl 2,4-difluoro-benzoate			η (20° C) = [0.42]			435.5		[117]	
193	4-(4-Propyl-cyclo-hexyl)phenyl 3,4-difluoro-benzoate			η (20° C) = [0.40]			417.7		[117]	
194	4-(4-Pentyl-phenyl)-cyclohexyl 3,4-difluoro-benzoate			η (20° C) = [0.43]			421.0		[117]	
195	4-(4-Alkylphenyl)-2-chlorophenyl 4-alkylcyclo-hexane-1-carboxy-lates	 $-C_mH_{2m+1}$ n=3, m=4 (55%)  (45%)		η (20° C) = [0.32]			414		[115]	
196	3',4'-Difluoro-4-biphenylyl 4-alkylcyclo hexane-1-carboxylates									
		n=3		η (20° C) = [0.34]			416.8		[118]	
		n=5		η (20° C) = [0.46]					[118]	
197	4-(4-Propylcyclo-hexyl)cyclo-hexyl 3,4-difluoro-benzoate			η (20° C) = [0.66]			[560]		[117]	
198	4-(4-Butylcyclo-hexyl)cyclohexyl 3-chloro-4-fluoro-benzoate			η (20° C) = [0.89]			399.5		[117]	

Table 1 (contd.)

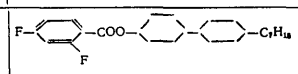
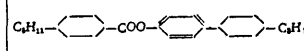
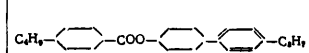
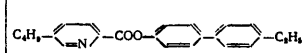
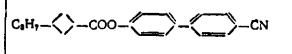
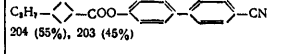
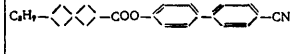
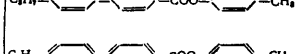
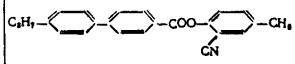
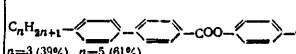
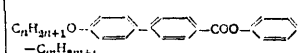
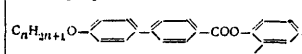
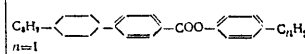
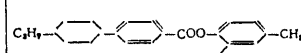
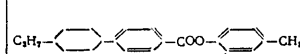
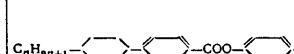
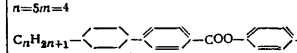
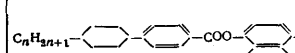
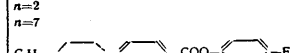
1	2	3	4	5	6	7	8	9	10	11
199	4-(4-Heptylcyclohexyl)-cyclohexyl 2,4-difluorobenzoate			η (20° C) = [0.32]			442.6		[117]	
200	4-(4-Propylcyclohexyl)phenyl 4-pentylcyclohexane-1-carboxylate			η (20° C) = (0.40)			466		[70]	
201	4-(4-Propylphenyl)-cyclohexyl 4-butylcyclohexane-1-carboxylate			η (25° C) = [0.3]					[35]	
202	5-Butyl-2-pyridyl 4'-ethylbiphenyl-4-carboxylate			η (20° C) = [10.5]					[119]	ΔH_m = 2323 K
203	*cis*-4'-Cyano-4-biphenylyl 3-n-propylcyclobutane-1-carboxylate			η (20° C) = [1.33]			336.2		[120]	
204	*trans*-4'-Cyano-4-biphenylyl 3-n-propylcyclobutane-1-carboxylate	 204 (55%), 203 (45%)		η (20° C) = [0.74] η (20° C) = [1.00]			414.7 374.3		[120] [120]	
205	4'-Cyano-4-biphenylyl 3-n-propylspiro-[3,3]heptane-1-carboxylate			η (20° C) = [1.70]			428.0		[120]	
206	4-Methylphenyl 4'-propylbiphenyl-4-carboxylate			η (20° C) = [0.81]			472		[35]	ΔH_m = 3660 K
207	3-Cyano-4-methyl phenyl 4'-propylbiphenyl-4-carboxylate			η (25° C) = [2.00]					[35]	
208	4-Ethoxyphenyl 4'-alkylbiphenyl-4-carboxylate	 n=3 (39%), n=5 (61%)		η (25° C) = [1.02]			500		[35]	ΔH_m = 3500 K
209	4-Alkylphenyl 4'-alkoxybiphenyl-4-carboxylate			η (25° C) = [1.60]					[35]	
210	4-n-Alkyl-2-cyanophenyl 4'-alkoxybiphenyl-4-carboxylate			η (25° C) = [3.10]					[35]	
211	4-Alkylphenyl 4-(4-propylcyclohexyl)-benzoates	 n=1 n=3		η (20° C) = [0.69] ν (20° C) = [0.60]			461 459		[35] [49]	ΔH_m = 2940 K
212	2,4-Dimethylphenyl 4-(4-propylcyclohexyl)-benzoate			η (25° C) = [1.44]			391		[35]	ΔH_m = 2610 K
213	2-Bromo-4-methylphenyl 4-(4-propylcyclohexyl)-benzoate			η (25° C) = [2.02]			392		[35]	ΔH_m=3590 K
214	4-Alkyl-2-cyanophenyl 4-(4-alkylcyclohexyl)-benzoate	 n=3/m=1 n=5/m=4		η (25° C) = [1.77] η (20° C) = [1.0]					[35] [56]	
215	4-Ethoxyphenyl 4-(4-alkylcyclohexyl)-benzoate	 n=3 (39%), n=5 (61%)		η (25° C) = [0.94]			492		[35]	ΔH_m = 3220 K
216	4-n-Alkoxy-2,3-dicyanophenyl 4-(4-alkylcyclohexyl)-benzoates	 n=2 n=7		η (20° C) = [2.1] η (20° C) = [1.8]			(377.2) (408.7)		[56] [56]	ΔH_m = 3220 K ΔH_m = 4580 K
217	4-Fluorophenyl 4-(4-pentylcyclohexyl)-benzoate			η (20° C) = [0.60]			[435]		[41]	

Table 1 (contd.)

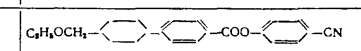
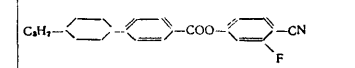
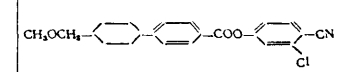
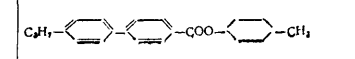
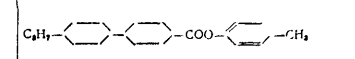
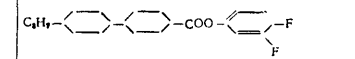
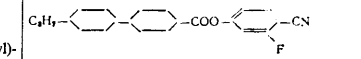
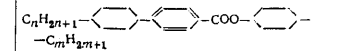
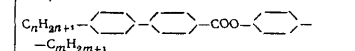
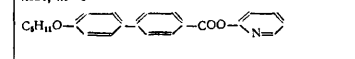
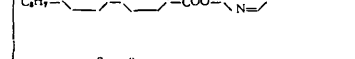
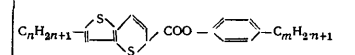
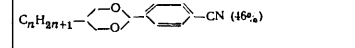
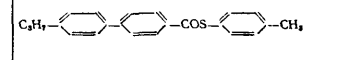
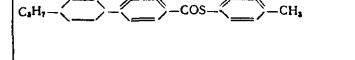
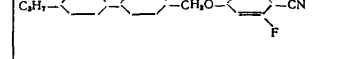
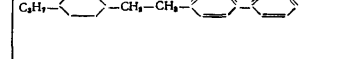
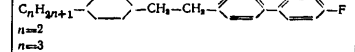
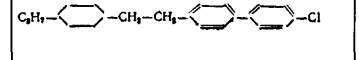
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218	4-Cyanophenyl 4-(4-ethoxymethylcyclohexyl)benzoate			η (20° C) = [1.28]			477		[121]	
219	4-Cyano-3-fluorophenyl 4-(4-propylcyclohexyl)benzoate			η (20° C) = [1.4]					[44]	
220	4-Cyano-3-chlorophenyl 4-(4-methoxymethylcyclohexyl)benzoate			η (20° C) = [1.88]			410		[44, 121]	
221	4-Methylcyclohexyl 4'-propylbiphenyl-4-carboxylate			η (20° C) = [0.30]			399		[35]	ΔH_m = 2460 K
222	4-Methylphenyl 4-(4-propylcyclohexyl)cyclohexane-1-carboxylate			η (20° C) = [0.16]			477		[35]	ΔH_m = 2990 K
223	3,4-Difluorophenyl 4-(4-propylcyclohexyl)cyclohexane-1-carboxylate			η (20° C) = [0.31]			426.2		[53]	
224	4-Cyano-3-fluorophenyl 4-(propylcyclohexyl)-cyclohexane-1-carboxylate			η (20° C) = [0.621]			484.2		[53]	
225	4-Alkylcyclohexyl 4-(4-alkylcyclohexyl)-benzoates	 n=2, m=3 n=3, m=3 n=4, m=3 n=5, m=3 n=5, m=1		η (20° C) = [1.30] η (20° C) = [1.30] η (20° C) = [1.29] ν (20° C) = [1.19] η (20° C) = [0.77]			406 433 423 427 402		[53] [53] [53] [70] [35]	ΔH_m = 3200 K
226	4-Alkylcyclohexyl 4-(4-alkylcyclohexyl)-cyclohexane-1-carboxylates	 n=3, m=1 n=4, m=3		η (20° C) = [0.19] ν (20° C) = [0.50]			428 457		[35] [49]	ΔH_m = 3890 K
227	2-Pyridyl 4'-n-pentyloxybiphenyl-4-carboxylate			η (25° C) = [1.95]			387		[35]	ΔH_m = 1840 K
228	2-Pyridyl 4-(4-n-propylcyclohexyl)cyclohexane-1-carboxylate			η (25° C) = [0.37]			391		[35]	ΔH_m = 4290 K
229	4-Alkylphenyl 2-alkyl-5*H*-thieno-[3,2-*b*]thiine-5-carboxylate	 n=3 (18%), n=5 (18%), n=7 (18%),  (46%)		ν (20° C) = [0,31]			335		[122]	
230	4-Methylphenyl 4-(4-propylphenyl)-thiobenzoate			η (25° C) = [0,79]			508		[35]	ΔH_m = 3080 K
231	4-Methylphenyl 4-(4-propylcyclohexyl)thiobenzoate			η (25° C) = [0,62]			497		[35]	ΔH_m = 2380 K
232	[4-(4-Propylcyclohexyl)cyclohexyl]-(4-cyano-3-fluorophenoxy)-methane			η (20° C) = [0,871]			429.5		[53]	
233	1-(4-Biphenylyl)-2-(4-propylcyclohexyl)ethane			η (20° C) = [0,22]					[123]	μ_{C-H} = 1.46 D r^3_H = 1.7 Å^3
234	1-Alkylcyclohexyl-2-(4'-fluoro-4-biphenylyl)-ethane	 n=2 n=3 n=4 n=5		η (20° C) = [0,245] η (20° C) = [0,25] η (20° C) = [0,36] η (20° C) = [0,315]					[123]	μ_{C-F} = 1.48 D, r^3_F = 2.5 Å^3
235	1-(4'-Chloro-4-biphenylyl)-2-(propylcyclohexyl)ethane			η (20° C) = [0,49]					[123]	μ_{C-Cl} = 1.56 D, r^3_{Cl} = 5.9 Å^3

Table 1 (contd.)

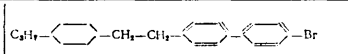
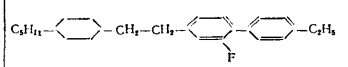
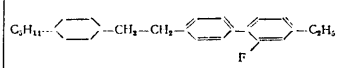
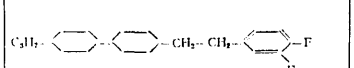
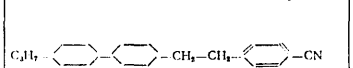
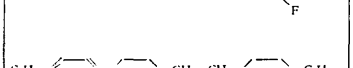
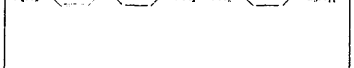
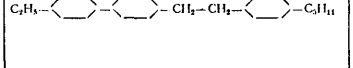
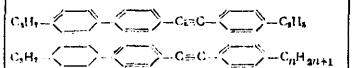
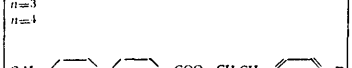
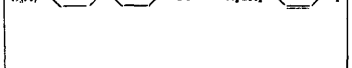
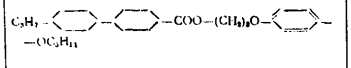
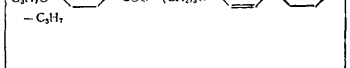
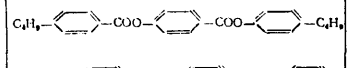
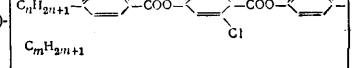
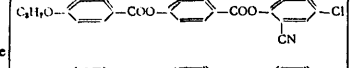
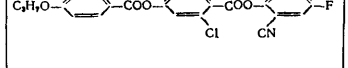
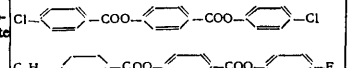
1	2	3	4	5	6	7	8	9	10	11
236	1-(4′-Bromo-4-biphenylyl)-2-(propylcyclohexyl)ethane			η (20° C) = [0.60]					[123]	μ_{C-Br} = 1.59 D, r^3_{Br} = 7.5 Å^3
237	1-(4′-Ethyl-2-fluoro-4-biphenylyl)-2-(4-pentylcyclohexyl)ethane			ν (20° C) = [0.24]			377.7		[124]	
238	1-(4′-Ethyl-2′-fluoro-4-biphenylyl)-2-(4-pentylcyclohexyl)ethane			ν (20° C) = [0.215]			376.2		[124]	
239	1-(3,4-Difluorophenyl)-2-[4-(4-propylcyclohexyl)cyclohexyl]-ethane			η (20° C) = [0.19]			391.2		[53]	ΔH_m = 3050 K
240	1-(4-Cyano-3-fluorophenyl)-2-[4-(4-propylcyclohexyl)cyclohexyl]-ethane			η (20° C) = [0.461]			446.1		[53]	
241	1-[4-(4-Butylphenyl)-cyclohexyl]-2-(4-pentylcyclohexyl)-ethane			η (25° C) = [1.03]			(456)		[125]	
242	1-[4-(4-Ethylcyclohexyl)cyclohexyl]-2-(4-pentylcyclohexyl)-ethane			η (25° C) = [0.71]			442		[125]	
243	4′-Ethyl-4-(4-propylphenyl)tolane			η (20° C) = [0.74]			[482]	Δn = [0.344]	[126]	
244	4′-Alkyl-4-(4-propylcyclohexyl)tolane	 n=3 n=4		η (20° C) = [0.31] η (20° C) = (0.479)			[465] 474	Δn = [0.309] Δn (25° C) = =0.253	[126] [27]	
245	β-(4-Fluorophenyl)-ethyl 4-(4-propylcyclohexyl)-cyclohexane-1-carboxylate			η (20° C) = [0.19]			356.7		[81]	
246	3-(4-Pentyloxyphenoxy)-1-propyl-4-(4-propylcyclohexyl)cyclohexane-1-carboxylate			η (20° C) = [0.88]			(348.7)		[127]	
247	3-[4-(4-Propylcyclohexyl)phenoxy]-1-propyl 4-propoxycyclohexane-1-carboxylate			η (20° C) = [0.45]			(339.5)		[127]	
248	4-n-Butylphenyl 4-(4-n-butylbenzoyloxy)benzoate		*a*	γ_1 (138° C) = 0.80	−0.8	3.95	452		[23]	
249	4-Alkylphenyl 4-(4-alkylbenzoyloxy)-2-chlorobenzoate			η (20° C) = (8)			420		[131]	
250	4-Chloro-2-cyanophenyl 4-(4-propoxybenzoyloxy)benzoate			η (20° C) = [1.36]			[241]		[129]	
251	2-Cyano-4-fluorophenyl 2-chloro-4-(4-propoxybenzoyloxy)-benzoate			η (20° C) = [1.30]			(372.5)		[129]	
252	Chlorophenyl 4-(4-chlorobenzoyloxy)benzoate		*a*	γ_1 (138° C) = 0.23	−10.8	3.83	513		[23]	
253	2-Cyano-4-fluorophenyl 4-(4-hexylcyclohexane-1-carbonyloxy)benzoate			η (20° C) = [1.31]			396.0		[129]	
254	2-Cyano-4-fluorophenyl 2-fluoro-4-(4-propylcyclohexane-1-carbonyloxy)benzoate			η (20° C) = [0.87]			392.2		[129]	

Table 1 (contd.)

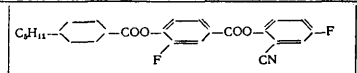
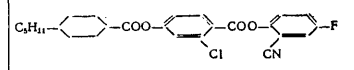
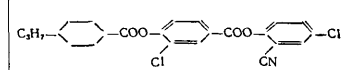
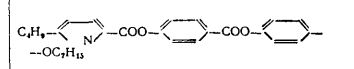
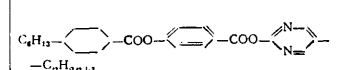
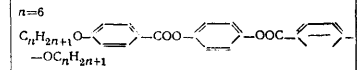
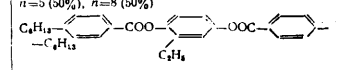
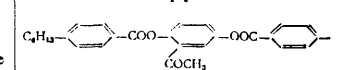
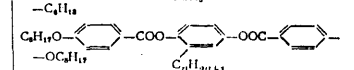
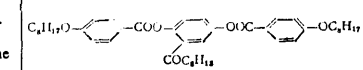
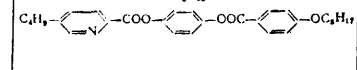
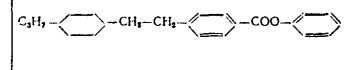
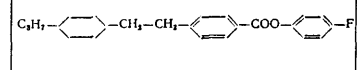
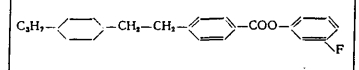
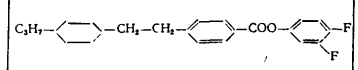
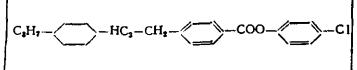
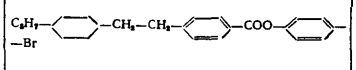
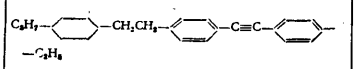
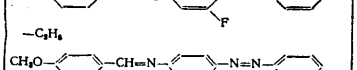
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255	2-Cyano-4-fluorophenyl 3-fluoro-4-(4-pentylcyclohexane-1-carbonyloxy)benzoate			η (20° C) = [1.18]			407.2		[129]	
256	2-Cyano-4-fluorophenyl 2-chloro-4-(4-pentylcyclohexane-1-carbonyloxy]benzoate			η (20° C) = [1.72]			[308]		[129]	
257	4-Chloro-2-cyanophenyl 3-chloro-4-(4-propylcyclohexane-1-carbonyloxy)benzoate			η (20° C) = [1.50]					[129]	
258	4-Heptyloxyphenyl 4-(5-butylpyridine-2-carbonyloxy)-benzoate			η (20° C) = [5.6]			434		[119]	ΔH_m = 2190 K
259	5-Alkyl-2-pyrimidinyl 4-(4-hexylcyclohexane-1-carbonyloxy)benzoate									
		n=5		η (20° C) = [1.38]			398.5		[130]	
		n=6		η (20° C) = [1.14]			[411]		[130]	
260	1,4-Bis(4-n-alkoxybenzoyloxy)-benzenes			ν (87° C) = 1.26			357		[132]	
		n=5 (50%), n=8 (50%)								
261	2-Ethyl-1,4-bis-(4-n-hexylbenzoyloxy)benzene		*a*	γ_1 (45° C) = 1.09		6.43	348.7		[133]	
			a	ν (25° C) = 2.83					[134]	
262	2-Acetyl-1,4-bis-(4-n-hexylbenzoyloxy)benzene			ν (25° C) = 6.61			360.1		[134]	
263	2-Alkyl-1,4-bis-(4-n-octyloxybenzoyloxy)-benzene									
		n=7		ν (87° C) = 6.42			352		[135]	
				ν (25° C)=9.6						
		n=8		ν (80° C) = 0.87			350		[128]	
264	2-Heptanoyl-1,4-bis-(4-n-octyloxybenzoyloxy)benzene			ν (87° C)=6,8			354		[135]	
265	4-(5-Butylpyridyl-2-carbonyloxy)-1-(4-octyloxybenzoyloxy)-benzene			η (20° C)=[5.5]			450		[119]	ΔH_m = 3454 K
266	Phenyl 4-[β-(4-n-propylcyclohexyl)-ethyl]-benzoate			η (20° C)=[0.19]					[136]	
				η (20° C)=[0.26]					[54]	
267	4-Fluorophenyl 4-[β-(4-n-propylcyclohexyl)-ethyl]-benzoate			η (20° C) = [0.2]					[136]	
				η (20° C) = [0.27]					[54]	
268	3-Fluorophenyl 4-[β-(4-n-propylcyclohexyl)-ethyl]-benzoate			η (20° C) = [0.27]					[54]	
269	3,4-Difluorophenyl 4-[β-(4-n-propylcyclohexyl)-ethyl]-benzoate			η (20° C) = [0.104]			405		[54]	ΔH_m = 3760 K
				η (20° C) = [0.30]					[54]	
270	4-Chlorophenyl 4-[β-(4-n-propylcyclohexyl)-ethyl]-benzoate			η (20° C) = [0.27]					[136]	
271	4-Bromophenyl 4-[β-(4-n-propylcyclohexyl)-ethyl]-benzoate			η (20° C) = [0.31]					[136]	
272	4-Ethyl-4'-(4-propylcyclohexylethyl)-tolane			η (20° C) = [0.056]			435.0	Δn = [0.332]	[126]	
273	4-Ethyl-2'-fluoro-4'-(4-propylcyclohexylethyl)-tolane			η (20° C) = [0.14]			423.0	Δn = [0.314]	[126]	
274	Methoxybenzylidene-4-aminoazobenzene		*a*	γ_1/ρ(174° C) = 0.043	−9.81	5.06	453		[33]	

Table 1 (contd.)

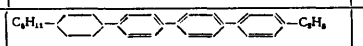
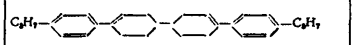
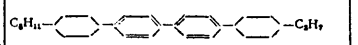
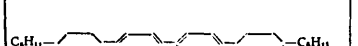
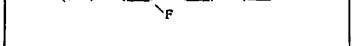
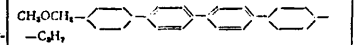
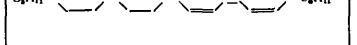
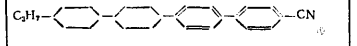
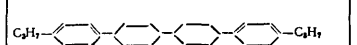
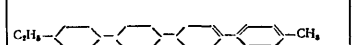
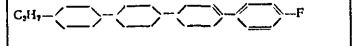
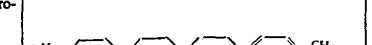
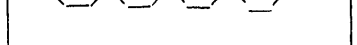
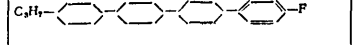
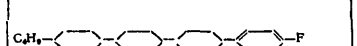
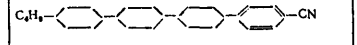
1	2	3	4	5	6	7	8	9	10	11
275	1-Ethyl-4″-(4-pentylcyclohexyl)-terphenyl			η (20° C) = [0.82]			[584]		[137]	
276	4,4′-Bis(4-propylphenyl)-2,3,5,2′,3′,6′-hexahydrobiphenyl			η (20° C) = [2.2]			532		[137]	
277	4-(4-n-Propylcyclohexyl)-4′-(4-n-pentylcyclohexyl)-biphenyl			η (20° C) = (0.42)			584		[70]	
278	2′-Fluoro-4,4′-bis-(4-n-pentylcyclohexyl)biphenyl			η (20° C) = [0.08] [0.50]			[628] [622]		[138]	in the matrix comprising phenylcyclohexanes in a matrix comprising biphenyls
279	4-(4-Propylcyclohexyl)-4′-(4-methoxymethylcyclohexyl)-biphenyl			η (20° C) = [3.7]			553		[103]	
280	4-Pentyl-4′-(4′-pentyl-4-bicyclohexylyl)-biphenyl			η (20° C) = [2.0]			[662]		[137]	
281	4-Cyano-4′-(4′propyl-4-bicyclohexylyl)-biphenyl			η (20° C) = [1.01]			[653]		[139]	
282	4,4′-Bis(4-propylphenyl)bicyclohexyl			η (20° C) = [0.83]			[501]		[137]	
283	4′-(4′-Ethyl-4-bicyclohexylyl)-2′,3′,4′,5′-tetrahydro-4-methylbiphenyl			η (20° C) = [0.81]			457		[137]	
284	4′-(4′-Propyl-4-bicyclohexylyl)-4-fluoro-2′,3′,4′,5′-tetrahydrobiphenyl			η (20° C) = [0.24]			452		[140]	
285	4″-Ethyl-4-(4-methylphenyl)-*p*-tercyclohexyl			η (20° C) = [0.81]			466		[137]	
286	4-(Fluorophenyl)-4″-propyl-*p*-tercyclohexyl			η (20° C) = [0.24]			452		[140]	
287	4″-Butyl-4-(3,4-difluorophenyl)-*p*-tercyclohexyl			η (20° C) = [1.36]			472		[140]	
288	4″-Butyl-4-(4-cyanophenyl)-*p*-tercyclohexyl			η (20° C) = [1.36]					[140]	
289	1-(4′-Propyl-4-bicyclohexylyl)-4-(4-ethylcyclohexyl)-benzene			η (20° C) = [2.5]			[541]		[137]	
290	2-(4-Butylcyclohexyl)-5-cyano-6-(4′-propyl-n-biphenylyl)-imidazo[2,1-*b*]-1,3,4-thiadiazole			γ_1(60° C) = [2.9]		[6.87]	>566		[141]	decomposes at T>566 K
291	4-(4′-Propyl-4-bicyclohexylyl)-phenyl 4-fluorobenzoate			η (20° C) = [3.2]			[850]		[142]	
292	4-(4′-Propyl-4-bicyclohexylyl)-phenyl 2,4-difluorobenzoate			η (20° C) = [0.83]			[610]		[117]	
293	4-(4′-Propyl-bicyclohexylyl)-phenyl 2,4-dichlorobenzoate			η (20° C) = [3.2]			[584]		[142]	

Table 1 (contd.)

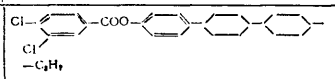
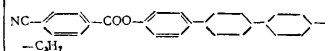
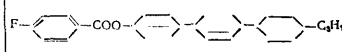
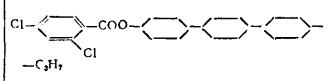
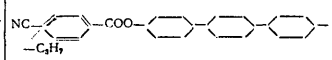
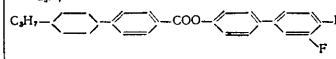
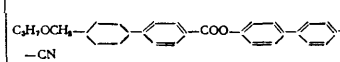
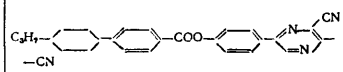
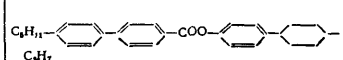
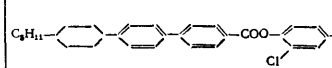
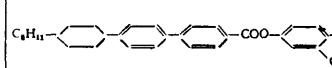
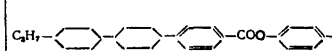
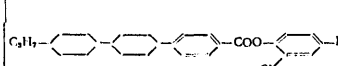
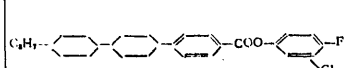
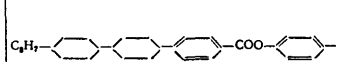
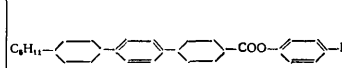
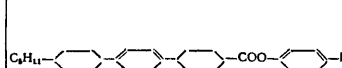
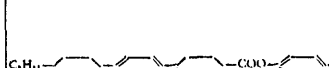
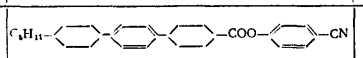
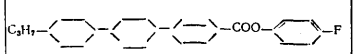
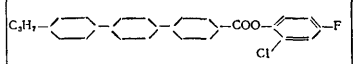
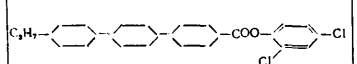
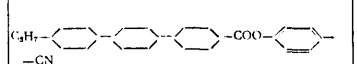
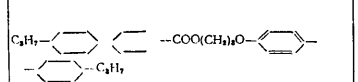
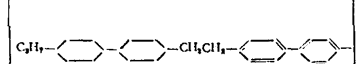
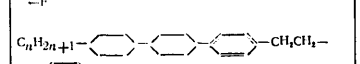
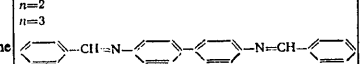
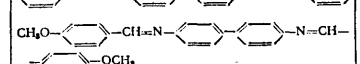
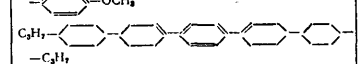
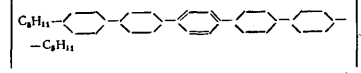
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294	4-(4'-Propyl-n-bicyclohexylyl)-phenyl 3,4-dichlorobenzoate			η (20° C) = [2.6]			[584]		[142]	
295	4-(4'-Propyl-4-bicyclohexylyl)-phenyl 4-cyanobenzoate			η (20° C) = [5.8]			[940]		[142]	
296	4''-Propyl-4-octahydro-*p*-terphenylyl 4-fluorobenzoate			η (20° C) = [1.9]			[570]		[142]	
297	4''-Propyl-4-octahydro-*p*-terphenylyl 2,4-dichlorobenzoate			η (20° C) = [2.6]			[584]		[142]	
298	4''-Propyl-4-octahydro-*p*-terphenylyl 4-cyanobenzoate			η (20° C) = [3.2]			[659]		[142]	
299	3',4'-Difluoro-4-biphenylyl 4(4-propylcyclohexyl)benzoate			η (20° C) = [1.12]			553,5		[118]	
300	4'-Cyano-4-biphenylyl 4-(4-propoxymethylcyclohexyl)-benzoate			η (20° C) = [1.82]			[584]		[121]	
301	4-(2,3-Dicyano-5-pyrazinyl)phenyl 4-(4-propylcyclohexyl)benzoate			η (20° C) = [0.78]			546		[143]	
302	4-(4-Propylcyclohexyl)-phenyl 4'-pentylbiphenyl-4-carboxylate			η (20° C) = [9.4]					[144]	
303	2-Chloro-4-fluorophenyl 4'-(4-pentyl cyclohexyl)-biphenyl-4-carboxylate			η (20° C) = [0.20]			552.8		[142]	in a matrix comprising biphenyls (compounds in a matrix comprising phenylcyclohexanes)
304	3-Chloro-4-fluorophenyl 4'-(4-pentylcyclohexyl)-biphenyl-4-carboxylate			η (20° C) = [1.29]			528.8		[142]	
305	4-Fluorophenyl 4-(4'-propyl-4-bicyclohexylyl)-benzoate			η (20° C) = [0.77]			[770]		[142]	
306	2-Chloro-4-fluorophenyl 4-(4'-propyl-4-bicyclohexylyl)-benzoate			η (20° C) = [0.64]			504.2		[142]	
307	3-Chloro-4-fluorophenyl 4-(4'-propyl-4-bicyclohexylyl)-benzoate			η (20° C) = [1.20]			515.5		[142]	
308	4-Cyanophenyl 4-(4'-propyl-4-bicyclohexylyl)-benzoate			η (20° C) = [2.9]			[850]		[142]	
309	4-Fluorophenyl 4-[(4-pentylcyclohexyl)phenyl]-cyclohexane-1-carboxylate			η (20° C) = [0.39]			[770]		[142]	
310	2-Chloro-4-fluorophenyl 4-[(4-pentylcyclohexyl)phenyl]-cyclohexane-1-carboxylate			η (20° C) = [0.39]			511.0		[142]	
311	3-Chloro-4-fluorophenyl 4-[(4-pentylcyclohexyl)phenyl]-cyclohexane-1-carboxylate			η (20° C) = [0.39]			495.4		[142]	

Table 1 (contd.)

1	2	3	4	5	6	7	8	9	10	11
312	4-Cyanophenyl 4-[(4-pentylcyclohexyl)phenyl]-cyclohexane-1-carboxylate			η (20° C) = [0.64]			511.0		[142]	
313	4-Fluorophenyl 4''-propyloctadecahydro-*p*-terphenyl-4-carboxylate			η (20° C) = [0.23]					[142]	
314	2-Chloro-4-fluorophenyl 4''-propyloctadecahydro-*p*-terphenyl-4-carboxylate			η (20° C) = [0.64]			532.9		[142]	
315	2,4-Dichlorophenyl 4''-propyloctadecahydro-*p*-terphenyl-4-carboxylate			η (20° C) = [0.64]			538.5		[142]	
316	4-Cyanophenyl 4''-propyloctadecahydro-*p*-terphenyl-4-carboxylate			η (20° C) = [1.29]			[850]		[142]	
317	3-[4-(4-Propylcyclohexyl)-phenoxy]propyl 4'-propylbicyclohexyl-4-carboxylate			η (20° C) = [0.78]			427		[127]	
318	1-(3',4'-Difluoro-4-biphenylyl)-2-(4'-propyl-4-bicyclohexylyl)-ethane			η (20° C) = [0.280]					[53]	
319	1-[4-(4'-Alkyl-4-bicyclohexylyl)-phenyl]-2-(4-propylcyclohexyl)ethane									
		$n=2$		η (20° C) = [0.55]			525.3		[145]	
		$n=3$		η (20° C) = [0.63]			517.6		[145]	
320	Dibenzylidenebenzidine		*a*	γ_1/ρ (259° C) = = 0.1350	−2.09	2.50	558		[33]	
321	Di-4-methoxybenzylidenebenzidine		*a*	γ_1/ρ (256.3° C) = =0.0243	−11.32	6.53	530		[33]	
322	1,4-Bis[4-(4-(propylcyclohexyl)-cyclohex-1-enyl]benzene			η (20° C) = [15.8]					[137]	
323	1,4-Bis-(4'-pentyl-4-bicyclohexylyl)-benzene			η (20° C) = [5.9]			[927]		[137]	

Remarks. The physical quantities (viscosity, temperature, activation energy, and double refraction), obtained by extrapolating the concentration variations of these quantities in the mixtures, are quoted in square brackets throughout the table.

*[1]The viscosities obtained by extrapolating their temperature variation are given in round brackets.

*[2]The temperatures of the "isotropic liquid—nematic liquid crystal" monotropic transition are given in round brackets.

*[3]The order parameter S or the double refraction Δn are quoted (also for reference), depending on the approximation formula used, taking into account the proportionality of the temperature variations of these physical quantities.

The order in which the liquid crystal substances have been arranged in terms of chemical classes approximately corresponds to the order adopted in the familiar Demus Tables for liquid crystals.[19] For substances belonging to one chemical class, for example, Schiff bases, the relative positions are determined by the polarity of the substituent (alkyl, alkoxy-, acyloxy-, cinnamate, CN, etc. groups). For representatives of a single chemical class which are members of a homologous series, the values of γ_1 or η are indicated at one or several temperatures at which these homologues exhibit mesogenic properties and also for the same temperature difference $\Delta T = T_{NI} - T$ or at the same reduced temperature, for example $T = 0.95T_{NI}$. The values of S or Δn are also listed for the same temperature difference. The temperature variation of the order parameter S is similar for different substances and can be described approximately by the formula

$$S \simeq S_0(1 - T/T^*)^{\beta}, \qquad (7)$$

where $T^* \simeq T_{NI} + (0.2-0.7)$, $\beta \simeq 0.18 \pm 0.02$, and $S_0 = 1.1-1.4$.[2,20,21]

Table 2. The viscosities of 4,4'-di-n-alkylazoxybenzenes C_nH_{2n+1}—⟨⟩—N=N(O)—⟨⟩—C_nH_{2n+1}.

n	γ_1				T_{NI}	Fitting formula	$\ln A_0$	E	S (ΔT=10° C) [22]	Refs.
	25° C	30° C	64° C	ΔT = 10° C						
4	0.476	0.15	—	0.67	304.1	*b*	—21.8	6.50	0.4956	[9]
	0.59			0.79	304	*a*	—21.6	6.27		[23]
5	—	0.948	0.168	0.28	339.8	*b*	—13.65	4.26	0.5918	[9]
	0.94	0.83			340.8	*a*	—13.13	3.90		[3]
6	—	0.783	—	0.38	326.4	*b*	—15.52	4.76	0.6105	[9]
		1.56		0.54	327	*a*	—22.4	6.96		[23]
7	—	—	0.291	0.36	343.3	*b*	—17.18	5.50	0.7041	[9]
8	—	—	0.388		339.4					[9]

Table 3. The viscosities of 4,4'-di-n-alkoxyazoxybenzenes [fitting formula *d*: $\ln(\gamma_1/S^2) = \ln A_0 + BS^2/(T - T_0)$]

$C_nH_{2n+1}O$—⟨⟩—N=N(O)—⟨⟩—OC_nH_{2n+1} (Fig. 1).

n	γ_1		T_{NI}	Fitting formula	$\ln A_0$	B, E, K	T_0	S (ΔT=10 °C) (Ref.21)	Refs.
	120° C	ΔT=10° C							
1	0.076	0.068	408.5	*d*	—1.711	10.41	336	0.5784	[18]
	0.064			*a*	—17.0	5600			[31]
	0.088			*a*	—17.68	7790			[33]
	0.068								[146]
	0.70	0.059		*a*	—17.72	5920			[23]
2	(0.39)	0.114	440.7	*d*	—1.455	10.61	386	0.6708	[18]
	(0.17)			*a*	—10.13	5029			[33]
3	0.10	0.152	396.8	*d*	—1.181	10.97	364	0.6330	[18]
4	0.18	0.136	409.9	*d*	—2.446	29.37	345	0.6706	[18]
5	0.10	0.182	396.4	*d*	—1.199	58.31	316	0.6427	[18]
6	0.16	0.174	402.3	*d*	—1.438	77.60	313	0.6810	[18]
7	0.205	0.295	397.4		—0.762	13.52	357.5	0.7118	[18]

Table 4. The viscosities of 4-alkoxybenzylidenebutylanilines

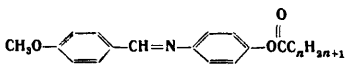
$C_nH_{2n+1}O$—⟨⟩—CH=N—⟨⟩—C_4H_9.

n	γ_1				T_{NI}	Fitting formula	$\ln A_0$	E	S (ΔT=10° C)	Refs.	Remarks
	25° C	44° C	57.4° C	ΔT=10° C							
1	1.09	0.192		0.552	318.3	*a*		5.78		[4]	
						b	—18.92	5.82	0.54 [28]	[4]	
	0.89				317.5			6.63		[5]	$E = \partial\gamma_1/\partial(T^{-1})$, $T = 0.92\,T_{NI}$
	0.96									[2]	
	0.98				319.6	*a*	—18.38	5.48		[3]	
	1.06				317.5			6.05		[13]	$E = \partial\gamma_1/\partial(T^{-1})$, $T = 0.92\,T_{NI}$
	0.85					*a*		5.69		[31]	
	0.75					*a*	—19.0	5.57		[23]	
		0.25								[48]	
2	—	0.781	0.45	0.229	352.5	*b*		4.78		[124]	
3		0.66	0.27		332.0	*a*	—21.0	6.53		[3]	
4			0.49		348.4					[3]	
		0.44	0.21	0.26						[141]	$\ln(\gamma_1/S^2) = -0.041 + 0.105\,S^2/(T-280)$
5			0.55		342.8					[3]	

For homologous series of certain substances, more detailed information about the viscosity and other physicochemical properties is given in Tables 2–13. The values of γ_1 and/or η, taken from different literature sources and treated by different procedures, are presented for certain substances. The results of the treatment based on the activation and free volume models are presented simultaneously for some of the substances. In a number of instances, the glass point T_g is indicated, which makes it possible to infer the value of γ_1 at low temperatures. In some cases, a general (alkyl, alkoxy-groups) rather than specific substitution is indicated and the values

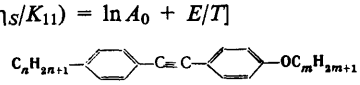
of γ_1 or η presented make it possible to infer only approximately the influence of molecular structure on the viscosity. Some of the results were obtained in studies of the properties not of individual substances but of mixtures of compounds referring to a single chemical class, which made it possible to extend greatly the range of existence of the mesophase while retaining a specific chemical structure. It has been shown[17] that, for the majority of NLC, the activation energy for rotational viscosity E is equal to or only 1.5–2 times greater than the enthalpy of fusion ΔH_m. The values of ΔH_m have therefore been listed for a number of substances making it possible to estimate the temperature variation of the viscosity.

Table 5. The viscosities of 4-anisilidene-4′-aminophenyl acetates[29] (fitting formula *b*)



n	γ_1		T_{NI}	$\ln A_0$	E	S ($T=0.95T_{NI}$) (Ref.28)
	90° C	$T=0.95\ T_{NI}$				
1	0.394	0.398	382.20	−17.81	6.26	0.5954
2	0.305	0.285	384.02	−17.14	5.96	0.5577
3	0.313	0.270	385.77	−14.58	5.03	0.6254
4	0.257	0.388	373.65	−15.31	5.28	0.6042
5	0.328	0.419	377.56	−17.44	6.12	0.6386
9	0.342	0.782	370.25	−23.71	8.42	0.6434

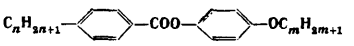
Table 6. The viscosities of 4-n-alkoxy-4′-n-alkyltolanes[148] [fitting formula: $\ln(\eta_S/K_{11}) = \ln A_0 + E/T$]



n	m	η_S/K_{11}		T_{NI}	E
		60° C	70° C		
4	2	0.45	0.33	353	1.08
5	2	0.40	0.355	353	1.08
6	2	0.47	0.405	349	1.16
8	2	0.53	0.45	352	1.16

The activation energy E and the enthalpy of fusion ΔH_m are quoted in Kelvin degrees to facilitate the use of the tables. All the temperatures are expressed in Kelvin degrees. The NLC clarification temperatures T_{NI}, listed in round brackets, indicate the monotropic isotropic liquid–nematic phase transition observed when the NLC is supercooled; the virtual isotropic liquid–nematic phase transition temperatures, calculated from the concentration variations of T_{NI} in NLC mixtures, are indicated in square brackets. In some cases, the anisotropies of the dielectric constant $\Delta\varepsilon$, the dipole moments μ expressed in Debyes (1 D = 10^{-18} CGSE units), the viscoelastic ratios γ_1/K_T, where $K_T = K_{11} + 1/4(K_{33} - 2K_{22})$ is the elasticity coefficient for the deformation in the twist-cell, as well as the times when the electrooptical response of the twist-effect t_{off} is switched off, which are of interest as regards practical applications, are indicated in the remarks. The cubes of the van der Waals radii r of the hydrogen, fluorine, chlorine, and bromine atoms are given in the 'remarks' for halogeno-derivatives. The relation between the parameters given in the 'remarks' and the viscosity of the NLC is discussed in Section IV.

Table 7. The viscosities of 4-alkoxyphenyl 4-n-alkylbenzoates[38] (Fig. 2) (fitting formula: $\ln\eta = \ln\eta_0 + E/T$)



No. of mixture	Mixture of composition*	$(n+m)_{av}$	L_{mol}^{av}**	η (25° C)	T_{NI}	$\ln\eta_0$	E
1	n=1, m=1 (11.2); n=3, m=2 (22.2); n=5, m=2 (28.3); n=1, m=4 (19.1); n=3, m=4 (19.2)	5.61	20.39	0.325	330.9	−15.6	4.32
2	n=1, m=1 (7.3); n=3, m=2 (14.8); n=5, m=2 (18.0); n=1, m=4 (11.9); n=3, m=4 (11.7); n=6, m=4 (36.4)	7.21	22.37	0.36	325.6	−15.2	4.23
3	Mixture 1 (50%), Mixture 6 (50%)	8.20	23.36	0.37	328.9	−15.8	4.42
4	n=5, m=2 (24.0); n=3, m=4 (16.0); n=4, m=6 (60.1)	8.82	24.31	0.38	324.6	−14.5	4.05
5	n=3, m=4 (12.0); n=6, m=4 (37.5); n=5, m=6 (50.4)	10.12	25.95	0.39	328.2	−14.4	4.02
6	n=3, m=6 (24.9); n=5, m=6 (33.1); n=3, m=8 (21.3); n=6, m=8 (20.7)	11.50	27.14	0.44	329.5	−15.1	4.27

*The contents of the mixture components in molar percentages are indicated in brackets.

**L_{mol}^{av} is the average length of the molecules in the mixture expressed in angstroms.

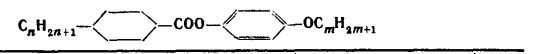
IV. Relation between the molecular structure of nematic liquid crystals and their viscosity

We shall trace the variation of the viscosities of NLC (rotational or dynamic) and their activation energies as the geometrical structure of the molecule and the distribution of electron density within it are varied, namely with increase in the length of the alkyl chain in the homologous series, with increase in the dipole moment of the molecular skeleton or of the connecting bridge, and after the introduction of heteroatoms or lateral substituents. We shall also attempt to indicate the causes of these changes.

In a homologous series with alkyl substituents, an even-odd correlation is observed for the values of γ_1 and η—in the even homologues the viscosity is greater than in the odd ones. The viscosities at the same remove from the nematic liquid crystal–isotropic liquid transition temperature and not viscosities at the same absolute temperature are compared for different homologues. Such variation of the viscosity with increase in the number of the homologue has been observed for dialkylazoxybenzenes (Table 2), cyanobiphenyls (Table 9), cyanophenylcyclohexanes (Table 11),

cyanobicyclohexanes (compound 92),† and cyanophenylpyridines (109). For tricyclic compounds, the even–odd alternation of the viscosity is much less pronounced, which has been confirmed by alkylcyclohexyl esters of alkylcyclohexylbenzoic acids (225). In the series with alkoxy- and acyloxy-substituents [dialkoxyazoxybenzenes (Table 3), alkoxycyanobiphenyls (Table 10), phenyl acetate derivatives (Table 5), and alkoxybenzylidenebutylanilines (Table 4)], the opposite situation obtains—the viscosity is greater for the odd homologues. Such variation of the viscosity in the homologous series is associated with the characteristic features of the molecular packing, which has been confirmed by theoretical calculations[18] (Fig. 1). As the alkyl chain is lengthened, the viscosity generally speaking increases, which can be seen particularly clearly in relation to alkoxyphenyl esters of alkylbenzoic and alkylcyclohexanecarboxylic acids (Tables 7 and 8, Fig. 2). If the molecular skeleton contains two benzene rings, the viscosity increases linearly with increase in the length f of the molecule. For Demus esters, where one benzene ring has been replaced by a cyclohexane fragment, the viscosity increases exponentially with increase in the length of the molecule. This suggests that, with increase in the contribution by repulsion forces, the free volume necessary for the migration and reorientation of the NLC molecules diminishes appreciably. For this reason, in the development of liquid crystal materials for matrix screens, where a greater steepness of the voltage-contrast characteristic (VCC) is required, phenyl benzoates with a long alkyl chain are preferred. They are not only characterised by a lower elasticity coefficient ratio K_{33}/K_{11}, ensuring a greater steepness of the VCC, but they also have a lower viscosity compared with that of Demus esters. The examples quoted above permit the conclusion that the activation energy for viscosity depends only slightly on the number of the homologue.

Table 8. The viscosities of 4-alkoxyphenyl 4-alkylcyclohexanecarboxylates[51] (Fig. 2) [fitting formula: $\ln\eta = \ln\eta_0 + B(T - T_0)$]

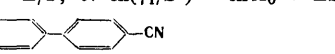


No. of mixture	Mixture composition*	$(n+m)_{av}$	L_{mol}^{av}**	η (25° C)	T_{NI}	$\ln\eta_0$	B	T_0
1	$n=5$, $m=1$ (49.7); $n=3$, $m=2$ (31.1); $n=5$, $m=2$ (19.2)	5.88	21.00	0.16	349.3	—4 94	203.9	233.0
2	$n=5$, $m=1$ (39.4); $n=5$, $m=2$ (13.5); $n=4$, $m=4$ (47.0)	7.07	22.70	0.205	344.8	—5.03	246.6	226.3
3	$n=5$, $m=1$ (28.3); $n=4$, $m=4$ (35.8); $n=5$, $m=6$ (35.9)	8.51	24.43	0.27	346.4	—6.03	442.0	204.4
4	$n=4$, $m=4$ (48.3); $n=5$, $m=6$ (51.7)	9.55	25.68	0.42	348.0	—5.86	385.6	220.1
5	$n=4$, $m=6$ (100)	10.00	26.15	0.51	343.2	—5.60	316.5	233.9

*The mixture components expressed in molar percentages are indicated in brackets.
**L_{mol}^{av} is the average length of the molecules in the mixture expressed in angstroms

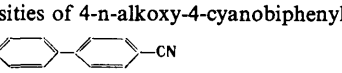
The influence of the increase in the polarisability of the substituent will be examined in relation to the alkenyl derivatives of phenylcyclohexanes (Table 13). The increase in the distance of the group containing a double bond from the molecular skeleton increases the polarisability of the solvent, which can be seen from the increase in the values of Δn, and also increases the rotational viscosity compared with pentylphenylcyclohexane. Nevertheless, the practical value for alkenyl derivatives is high, since they have shorter twist-effect switch-over times owing to the smaller viscoelastic ratio. By comparing the viscosities of a series of substances (compounds 5–8), we also see that an increase in the polarisability of the substituents (alkyl, acetoxy-, cinnamoyloxy-, and cyano-groups) leads to an increase in viscosity (see also Figs. 3 and 4).

Table 9. The viscosities of 4-n-alkyl-4′-cyanobiphenyls [fitting formula *b*: $\ln(\gamma_1/\Delta n) = \ln A_0 + E/T$; *e*: $\ln(\gamma_1/S^2) = \ln A_0 + ES/T$]



n	γ_1 25° C	γ_1 $\Delta T = 5$ K	T_{NI}	Fitting formula	$\ln A_0$	E	S ($\Delta T = 5$ K)	Refs.
5	0.82							[4]
	0.82		308.2	*b*	—20.0	5.84		[16]
	0.76	0.55	308.4	*e*	—0.095	0.88	0.5326	[8]
6	0.56	0.65	302.1	*e*	0.389	0.82	0.4928	[8]
			303.1			5.41		[3]
7		0.48	315.9	*e*	—1.402	1.65	0.5416	[8]
8	1.11		313.7	*b*	—15.8	5.31		[4. 16]
	(T = 34° C)	0.72	313.6	*e*	0.329	0.63	0.5585	[8]
9		0.48	322.6					[8]

Table 10. The kinematic viscosities of 4-n-alkoxy-4-cyanobiphenyls[65]



n	3	4	5	6	7	8	9
ν (70 °C), S	0.15	0 085	0.18	0.12	0.10	0.155	0.12 (80° C)
T_{NI}	347.7	351.2	312.2	330.2	327.2	327.7	337.2

A quantitative relation between the viscosities η and the bulk and dipole moment of the substituent has been obtained for halogenoderivatives of propylcyclohexylbiphenylylethane (compounds 233 to 236). On successive replacement of the hydrogen atom by F, Cl, and Br atoms, $\ln\eta$ increases in proportion to the dipole moment of the bond between the carbon and halogen atoms or in proportion to the cube of the van der Waals radius of the substituent (Fig. 5). Bearing in mind that the halogen substituent is rigidly bound to the molecular skeleton, this result can be interpreted also from the standpoint of the influence of the dipole moment of the molecular skeleton on the viscosity (the dipole moments of molecules or their fragments were taken from the papers of Minkin and co-workers[151,152] or calculated in accordance with their procedures). The correlation between the dipole moments of substituents rigidly attached to the molecular skeleton and the dynamic or kinetic viscosity of the NLC can be seen also in relation to the bicyclic and tricyclic derivatives of phenylcyclohexane (compounds, 60, 61, 66, 69 and 135, 138, 140, 141). We may note that alkylphenylalkylcyclohexanes (compounds 60) have the smallest viscosities among the known NLC and also the smallest

†The numbers of the compounds in Table 1 are indicated in brackets.

glass points T_g = 159 K, as a result of which they are used as the main components in the development of liquid crystal materials with a fast response at low (down to −60 °C) temperatures.

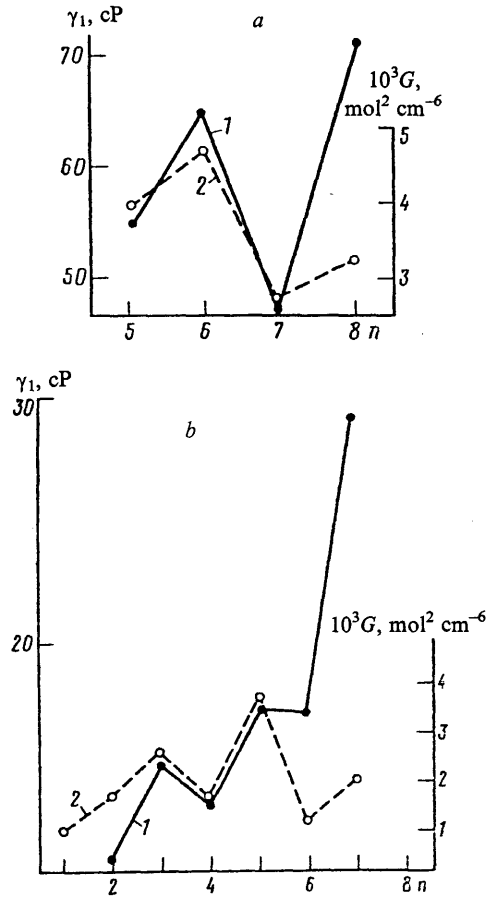


Figure 1. Correlation between the odd-even variation of the rotational viscosity γ_1 (line *1*) and the parameter G (line *2*) characterising molecular packing for alkylcyanobiphenyls (52) ($\Delta T = T_{NI} - T$ = 5 °C) (*a*) and dialkoxyazoxybenzenes (line *3*) (ΔT = 10 °C) (*b*). $G = [V_N(V^a - V_N)]^{-1}$, where V_N is the molar volume in the nematic phase and V^a is the molar volume in the nematic phase extrapolated from the isotropic phase.[18]

The influence of the dipole moment of the bridge connecting the benzene rings on the rotational viscosity and its activation energy can be examined with the aid of Table 14. The tabulated data not only confirm the correlation established between the dipole moment of the molecular skeleton and the viscosity of the NLC but also permit the claim that the distribution of electron density within the molecule influences significantly also the activation energy, which characterises the intermolecular interaction energy.

Table 15 presents the viscosity and dielectric characteristics of the NLC whose molecules contain a heterocyclic fragment. Although the dipole moments of the heterocycles themselves are almost the same, their introduction into the NLC molecule alters significantly the dipole moment of the latter, which has an appreciable effect on the anisotropy of the dielectric constant Δε; furthermore, a correlation is again observed between Δε and γ_1. The quantities γ_1 and E are influenced also by the positions of the heteroatoms (see the data for phenylpyridines—compounds 110, 111, 114, and 115 in Table 1). It can be seen in relation to dioxane, oxathiane, and dithiane derivatives (103 − 105) that the replacement of one and then the second oxygen atoms in the dioxan fragment by sulphur atoms increases the viscosity.

Table 11. The kinematic viscosities of 1-alkyl-4-(4-cyanophenyl)-cyclohexanes[150]

C_nH_{2n+1}—⟨⟩—⟨⟩—CN

n	1	2	3	4	5	6
ν (20 °C), S	0.18	0.19	0.18	0.22	0.21	0.28
n	7	8	9	10	11	12
ν (20 °C), S	0.265	0.33	0.325	0.40	0.40	0.47

Note. The values of ν were obtained by extrapolating their temperature variation.

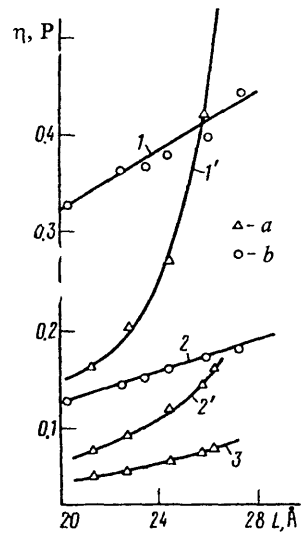


Figure 2. Dependence of the dynamic viscosity η on the average length of the molecule L in mixtures of phenylbenzoates (18) (*b*) and cyclohexyl benzoates (35) (*a*) at different temperatures (°C): (1) and (1′) 25; (2) and (2′) 45; (3) 65.

The close relation between the viscosity and the anisotropy of the dielectric constant is indicated by Fig. 6, where the viscosities of more than 80 materials produced by the Swiss firm Hoffmann-La Roche are plotted along the ordinate axis against the values of Δε for the same materials along the abscissa axis. The statistical mean

Table 12. The rotational and dynamic viscosities of 1-alkyl-4-(4-cyanophenyl)cyclohexanes [fitting formula *a*: $\ln\gamma_1 = \ln A_0 + E/T$; *b*: $\ln[\gamma_1/(\Delta n)^2] = \ln A_0 + E/T$; *f*: $\ln[\gamma_1/(\Delta n)^2] = \ln A_0 + E/(T - T_0)$]

C_nH_{2n+1}—⟨⟩—⟨⟩—CN

n	γ_1		η (20° C)	T_{NI}	Fitting formula	$\ln A_0$	*E*	Δn ($T = 0.95T_{NI}$)	T_0	Refs.	Remarks
	25° C	$T = 0.95T_{NI}$									
3			0.193							[149]	
5	0.97		0.210	328.2	*b*	—5.8	2.76	0.149		[16, 149]	
					f				247.4	[16]	more accurate fitting formula
	1.28 (22° C)				*a*		4.87			[76]	
	0.80			328.2	*a*		4.48			[3]	
7	1.40	0.69	0.268	330.2	*b*	—10.05	3.25	0.102		[16, 149]	
	1.09				*f*	—5.52	0.529		207.8	[16]	more accurate fitting formula

straight line is described by the equation $\eta = 0.105 + 0.02\,\Delta\varepsilon$ and virtually all the $\eta(\Delta\varepsilon)$ points fit between the two straight lines $\eta_{max} = 0.22 + 0.02\,\Delta\varepsilon$ and $\eta_{min} = 0.055 + 0.02\,\Delta\varepsilon$.

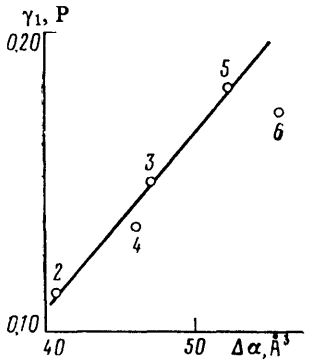


Figure 3. Dependence of the rotational viscosity γ_1 of dialkoxyazoxybenzenes ($C_nH_{2n+1}O$—⟨⟩—N=N(O)—⟨⟩—OC_nH_{2n+1}) on the anisotropy of the polarisability of the molecule. The numerals represent the numbers of the homologues.

Table 16 is a compilation of data for polar compounds without heterocyclic fragments. The replacement of the CN groups by NCS diminishes the viscosity of the liquid crystal, although the twist-effect switch-over times remain the same. The introduction of the ethane bridge instead of a single bond or the replacement of the alkyl group by an alkenyl group with the double bond remote from the cyclohexane fragment did not alter t_{off} either, although both these factors increase appreciably the viscosity of the NLC. On the other hand, the combination of two factors acting in opposite directions—the introduction of the thiocyanoto-group and of the ethane bridge—leads to an appreciable decrease in γ_1 and t_{off} (apparently as a consequence of the less dense molecular packing and the absence of a dipole moment in the bridge).

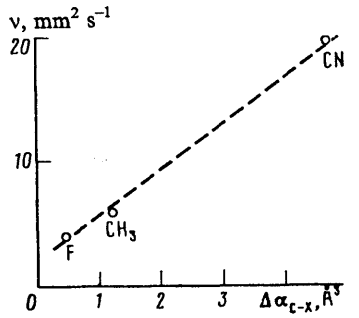
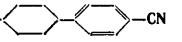
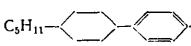
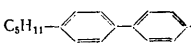


Figure 4. Dependence of the kinematic viscosity ν of phenylcyclohexane derivatives (C_3H_7—⟨⟩—⟨⟩—X) on the anisotropy of the polarisability of the C—X bond, where X = F, CH_3, or CN.

Although the substitution of a hydrogen atom by a fluorine atom is actually referred to as isogeometrical,[153] the increase in the electronegativity of the molecule occurring thereupon diminishes the thermal stability of the mesophase and increases the coefficient of internal friction, which can be seen in relation to the fluorinated derivatives of the alkylphenyl esters of alkylcyclohexanecarboxylic acids (compounds 34), tolanes (16), biphenyls (53, 54), and biphenylcyclohexanes (136, 137). However, the simultaneous introduction of fluorine in the *meta*- and *para*-positions promotes a significant decrease in viscosity. Thus the difluorophenyl derivatives of bicyclohexylethane (239 and 318) have almost the lowest viscosities among the tricyclic and tetracyclic substances respectively. It is also

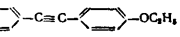
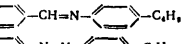
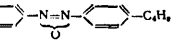
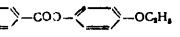
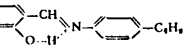
Table 13. The viscosities of 1-alkenyl-4-(4-cyanophenyl)cyclohexanes[50,78] (fitting formula: $\ln\gamma_1 = \ln\gamma_0 + E/T$)

C_nH_{2n+1}—CH=CH—C_mH_{2m}——CN

n, m	γ_1 (22° C)	η (22° C)	γ_1/K_T (22 °C), 10^{-10} s m^{-2}	T_{NI}	ln γ_0	E	Δn ($\Delta T = 10°$ C)	t_{off} (22 °C), ms
$n = 3$, $m = 0$	1.34	0.221	1.11	331.7	—16.62	4.99	0.116	40
$n = 3$, $m = 0$ (60%); $n = 2$, $m = 0$ (40%)	1.21	0.228	1.23	325.4	—16.32	4.87	0.117	42
$n = 3$, $m = 0$ (60%); $n = 0$, $m = 2$ (40%)	1.19	0.209	1.15	324.1	—16.33	4.87	0.115	37
$n = 1$, $m = 2$ (60%); $n = 0$, $m = 2$ (40%)	1.50	0.190	0.83	338.4	—15.73	4.76	0.127	32
$n = 3$, $m = 0$ (60%); $n = 0$, $m = 3$ (40%)	0.97	0.278	1.59	308.3	—20.10	5.92	0.105	67
$n = 0$, $m = 5$	0.99		2.02	305.4	—14.65	4.32	0.086	
C_5H_{11}——CN	1.28	0.215	1.14	328.1	—16.67	4.99	0.099	43
C_5H_{11}——CN	1.01	0.263	1.18	308.1	—21.24	6.27	0.178	55

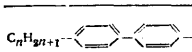
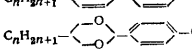
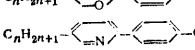
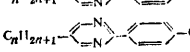
noteworthy that compounds containing the CN group in the *para*-position and fluorine in the *meta*-position have a higher positive value of $\Delta\varepsilon$ than the analogous compounds without fluorine. For example, $\Delta\varepsilon = +12$ for cyanophenyl heptylbenzoate, while $\Delta\varepsilon = +49.7$ (22, 23) for the analogous 4-cyano-3-fluorophenyl ester, which is associated with the fact that the fluorine atom prevents the dimerisation of the polar molecules leading to the partial cancelling of their dipole moments. This property makes it possible to reduce significantly the threshold potential of the electrooptical effect. Substances with fluorine or chlorine in the terminal position (compound 66 is an analogue) are frequently introduced into the liquid crystals in order to reduce their viscosity.[154]

Table 14. The influence of the dipole moment μ of the skeleton of a molecule having a bridging fragment on the rotational viscosity γ_1 and the activation energy E.

Compound	γ_1, P (25 °C)	E (10^4 K)	μ, D
C_4H_9——OC_5H_9	(0.9)	3.6	0—0.3
CH_3O——C_4H_9	1.09	5.82	1.57
CH_3O——C_4H_9	1.57	4.55	1.70
C_4H_9——OC_5H_9	2.20	5.11	1.90
CH_3O——C_4H_9	(6)	7.35	2.39

The sulphur atom is less electronegative than the oxygen atom and the substitution of oxygen by sulphur in the COO ester bridge therefore tends to increase the thermal stability of the mesophase and to increase slightly the viscosity, which can be seen from a comparison of the alkoxyphenyl and alkoxythiophenyl esters of alkylcyclohexanecarboxylic acids (35, 44) and methylphenyl and methylthiophenyl esters of propylbiphenylcarboxylic and propylcyclohexylbenzoic acids (compounds 206 and 230, 211 and 231).

Table 15. The influence of a heterocyclic fragment having a dipole moment μ on the anisotropy of the dielectric constant $\Delta\varepsilon$ and the rotational viscosity γ_1.

Compound	γ_1, P (25 °C)	μ, D	$\Delta\varepsilon$ ($\Delta T = 10$ K)
C_nH_{2n+1}——CN	1.02	~0	11.73
C_nH_{2n+1}——CN	1.34	2.14÷2.55	13.30
C_nH_{2n+1}——CN	1.84	2.11—2.20	16.60
C_nH_{2n+1}——CN	2.01	2.0÷2.42	19.72

When liquid crystals are selected for the observation of the dynamic scattering effect or in order to obtain a low frequency of the inversion of the sign of the anisotropy of the dielectric constant, substances with a large transverse dipole moment, usually with one or two lateral CN groups, are used. On comparing the viscosities of 4-methylphenyl 4'-propylbiphenyl-4-carboxylate and 3-cyano-4-methylphenyl 4'-propylbiphenyl-4-carboxylate (compounds 206 and 207), the analogous propylcyclohexyl derivatives (211, 214), as well as the 4-ethoxyphenyl 4'-alkylcyclohexylbenzoate and the analogous 2,3-dicyanophenyl benzoate (215, 216), we see that the increase in

viscosity (by a factor of 2.2–2.5 compared with the viscosities of substances without lateral groups) is independent of the number of CN groups. The less polar methyl group increases the viscosity to a lesser extent (compound 212). By increasing the length of the alkyl chains along the long molecular axis, it is in general possible to reduce to a minimum the increase in viscosity caused by the introduction of the CN group (see the data for compound 214, where the viscosities of two derivatives of 3-cyanophenyl benzoate with overall lengths of the alkyl chains equivalent respectively to 4 and 9 methyl groups are compared). Evidently the presence of lateral cyano-groups in bicyclic compounds affects the viscosity to a greater extent (35, 42).

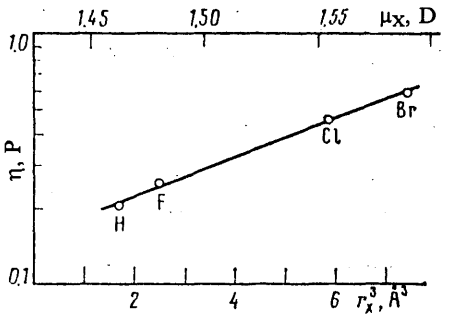


Figure 5. Dependence of the dynamic viscosity η of halogeno-derivatives on the van der Waals radius of the substituent (r_X) and the C–X bond dipole moment (μ_X).

The introduction of lateral alkyl and alkoxy-groups in the *meta*-position as in bisalkyl(or alkoxy)benzoyloxybenzenes (compounds 260–264) leads to an appreciable increase in the viscosity of the NLC for purely geometrical reasons, alkoxy- and acyloxy-groups giving rise to a greater increase in viscosity than alkyl groups. The viscosity of derivatives of bicyclooctane (compounds 96–99) is high mainly because of geometrical reasons—as a consequence of the denser molecular packing due to the presence of bulky fragment. We may note yet again that this does not affect the character of the intermolecular interaction and the activation energy for phenylbicyclooctanes is just as low as for phenylcyclohexanes. The influence of molecular packing on the rotational viscosity of bicyclic polar compounds is illustrated in Fig. 7.

In order to enhance the amplitude modulation of light using the dynamic light scattering effect or phase modulation in conjunction with *S*- and *B*-effects in image transformation problems in defectoscopy a high double refraction Δn is needed. Tolane derivatives (compounds 13–16, 243, 244, 272, 273) have a low viscosity combined with a high value of Δn. It is seen from Table 6 that tolane derivatives have a low activation energy for the viscoelastic ratio, which is the reason for the weak temperature dependence of the electrooptical response switch-over times.

The influence of the form of the skeletal fragment and also of the position of the substituent in the *cis*- and *trans*-position can be observed in relation to derivatives of spiro[3.3]heptane (compound 205), *cis*- and *trans*-cyclobutanes (203, 204), bicyclohexanes (88–94), and cyclohexylcyclohexenes (86, 87). In relation to derivatives of cyclohexene (134, cf. with 132, 141; 276, cf. with 282) and naphthalene (compounds 126–128), we see that the hydrogenation of the bonds in the molecular skeleton does not always reduce the

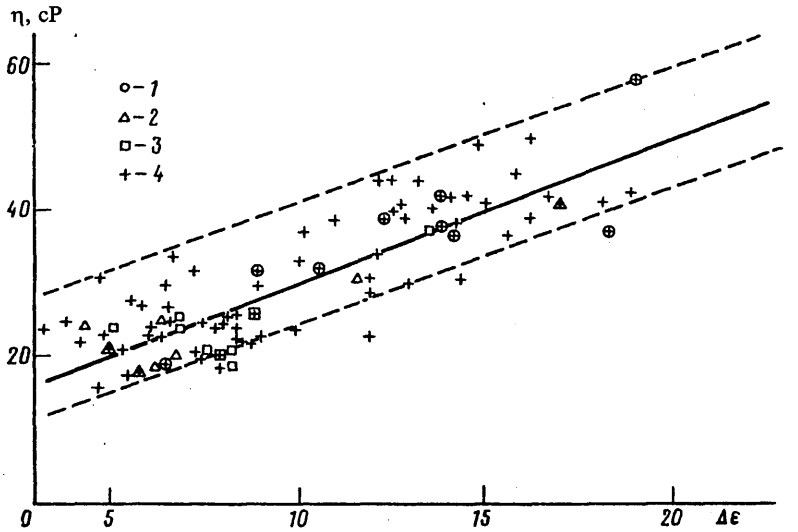


Figure 6. Dependence of the viscosity η of Hoffmann-La Roche liquid crystals on the anisotropy of the dielectric constant Δε: continuous line—averaging with respect to all the liquid crystals; dashed lines—η_{max} and η_{min} (see text); (*1*) liquid crystals with 1 : 4 multiplexity; (*2*) liquid crystals for TPT-matrices; (*3*) liquid crystals for the supertwist-effect; (*4*) remaining liquid crystals.

viscosity. Analysis of the data for this group of substances reveals a very small viscosity of the methyl ether of propylbicyclohexylmethanol (90) combined with a fairly high clarification temperature. The unusual structure of their side chain is responsible for this property.

Table 16. The rotational viscosities (γ_1), activation energies (E), and times at which the twist-effect is switched off (t_{off}) for bicyclic polar compounds.

Compound	γ_1, P	E (10^4 K)	t_{off}, ms
C_5H_{11}–⟨⟩–⟨⟩–CN	1.28	4.87	43
C_5H_{11}–⟨⟩–⟨⟩–NCS	0.83	4.30	41
CH_3–CH=CH–C_6H_4–⟨⟩–⟨⟩–CN, CH_3–CH–C_6H_4–⟨⟩–⟨⟩–CN	1.50	4.76	32
C_2H_5–CH=CH–C_6H_4–⟨⟩–⟨⟩–NCS	1.00	4.82	32
C_5H_{11}–⟨⟩–CH_2–CH_2–⟨⟩–CN	1.80	4.87	43
CH_3–CH=CH–⟨⟩–CH_2–CH_2–⟨⟩–CN, CH_2=CH–C_6H_4–⟨⟩–CH_2–CH_2–⟨⟩–CN	2.15	4.99	29
C_2H_5/C_6H_{13}–⟨⟩–CH_2–CH_2–⟨⟩–NCS	1.05	4.82	21
C_5H_{11}/C_7H_{15}–⟨⟩–COO–⟨⟩–CN	2.69	4.43	29
C_5H_{11}–⟨⟩–⟨⟩–CN	1.01	6.27	55
C_4H_{11}/C_7H_{15}–⟨⟩–CH=N–⟨⟩–CN	3.60	5.36	39
C_5H_{11}/C_7H_{15}–⟨⟩–COO–⟨⟩–CN	4.10	6.48	70

The higher viscosity of the polar cyclohexylcyclohexane derivative (92) combined with a higher clarification temperature compared with the phenylcyclohexane analogue (69) suggests a denser packing of the bicyclohexane molecules, despite the fact that repulsion forces play the main role in the formation of the mesophase in these substances. A similar increase in viscosity and in activation energy can be seen also in the tricyclic derivatives of pyrimidine (183 and 185) having a cyclohexane fragment next to the CN group. At the same time, the lower values of T_{NI} for these compounds compared with the benzonitrile analogue (184) show that in such cases the molecule is apparently non-linear. Among substances consisting of tricyclic polar molecules, alkylcyclohexylpyrimidinylbenzonitrile (184) is optimal as regards viscosity and temperature for the preparation of liquid crystal materials.

The molecular shape and hence the viscosity and thermal stability of the test substance depend to a large extent on the atom of the –COO– bridge group to which the cyclohexane fragment is linked, which is clearly confirmed by many examples [compare the viscosities of the cyanophenyl esters of alkylcyclohexanecarboxylic acids and alkylcyclohexyl esters of cyanobenzoic acids (39 and 48, 40 and 49), alkylcyclohexyl alkylcyclohexylbenzoate and alkylcyclohexylphenyl alkylcyclohexanecarboxylate (200 and 225), the alkylphenyl and alkylcyclohexyl esters of alkylphenylbenzoic acids (206 and 221), and the analogous esters of alkylbicyclohexanecarboxylic acids (222 and 226)]. The comparison shows that substances with the C_nH_{2n+1}–⟨⟩–O– fragment have a lower viscosity and lower clarification temperature compared with substances having the C_nH_{2n+1}–⟨⟩–O– fragment. Among tricyclic non-polar compounds, methylphenyl propylbicyclohexanecarboxylate has the lowest viscosity and a fairly high clarification temperature, which makes it promising for practical application. A lower viscosity of alkoxy-compounds with –COO– bridges is achieved when the benzene ring is located between two oxygen atoms [compared with data for alkoxyphenyl akylbenzoates and alkylphenyl alkoxybenzoates (18 and 19) and also for alkoxyphenyl akylbiphenylcarboxylates and alkylphenyl alkoxybiphenylcarboxylates (208 and 209)].

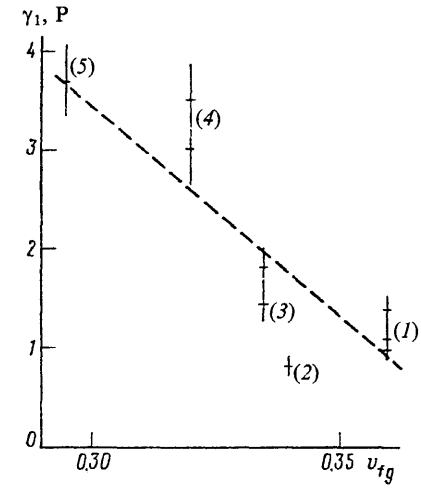


Figure 7. Relation between the rotational viscosity γ_1 of bicyclic polar compounds and the geometrical free volume $v_{fg} = 1 - k_p$, where k_p is the molecular packing coefficient determined from density measurements:

(*1*) $-C_nH_{2n+1}$–⟨⟩–⟨⟩–CN, (*2*) $-C_nH_{2n+1}$–⟨⟩–⟨⟩–CN,

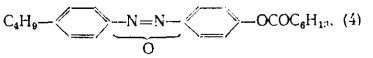
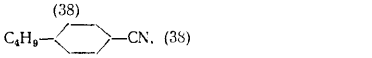
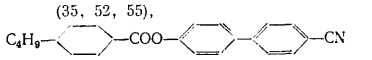
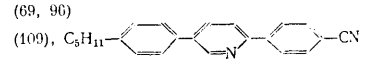
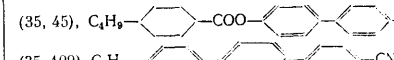
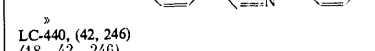
(*3*) $-C_nH_{2n+1}$–⟨N⟩–⟨⟩–CN, (*4*) $-C_nH_{2n+1}$–⟨⟩–⟨⟩–CN,

(*5*) $-C_nH_{2n+1}O$–⟨⟩–⟨⟩–CN

By way of principal conclusion, we emphasise that the viscosity of NLC is determined by the following molecular characteristics: the size and shape of the molecule, the polarisability of the substituents, and the dipole moment of the molecular skeleton. The tables can serve as a guide for the specific synthesis of new substances and the selection of existing compounds for the creation of liquid crystal materials with a specified fast response. We may note that the viscosities of liquid crystals in mixtures are not always additive. The properties of mixtures of NLC and liquid crystal materials have been

described[133,155–158] and constitute the subject of a separate study. For reference purposes, Table 17 presents the kinematic viscosities of various Soviet and foreign materials.

Table 17. The kinematic viscosities of Soviet and foreign liquid crystal materials.[156–158]

Designation	Compound •	$10^3\ \nu$, S (20 °C)
LC-440	 (4)	37.07
LC-616	LC-440, (22)	41.8
LC-654	»	51.4
LC-805	(38)	51.96
LC-910	 (38)	30
LC-609	(52)	32.31
LC-807	(52, 55, 132)	69.58
E7 (BDH, England)	(52, 132)	44
LC-1282	(35, 52, 55), 	52
LC-1289	ditto	41
LC-1290	»	43
P-52 (Chisso, Japan)		40
SP-706C (DNT, Japan)		32.13
E-202, 210 (BDH)		24.7
LC-1350	(35, 61, 69, 138, 143)	22
LC-1351	ditto	19
LC-1390	(60, 61, 69, 135, 143)	24.45
LC-1391	ditto	21.30
NP-1565 (Merck, FRG)	»	19
ZLI-1957/5 (Merck, FRG)		18
ZLI-2471 (Merck, FRG)		17
ZLI-2081		14
RO-3652		η = 16 cP (T = 22° C)
RO-2915 (Hoffmann – La Roche, Switzerland)		η = 22 cP (T = 22° C)
LC-1133	(69, 96)	36.7
LC-1144	(109), 	78.3
LC-1281	(35, 45), 	32
LC-1283	(35, 109), 	66
LC-1285	»	58
LC-999	LC-440, (42, 246)	36.4
LC-1000	(18, 42, 246)	62.1

*The numbers of the compounds in Table 1 are indicated in round brackets.

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