Liquid Crystal Polymers. 3. Thermotropic Rigid Aromatic Copolyesters with Bisphenol Spacers

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ABSTRACT: A series of aromatic polyesters based on either poly(chloro-*p*-phenylene terephthalate) or poly(methyl-*p*-phenylene terephthalate) modified by incorporation of various amounts of bisphenols of different structures was prepared and their thermotropic liquid crystal properties were studied by several methods: (1) visual observation of stir opalescence of the polymer melts, (2) examination of melt birefringence on a polarizing microscope, (3) studies of small-angle light scattering characteristics, and (4) characterization by wide-angle X-ray diffraction. It was found that the steric effects of nonlinear bisphenol modifiers were the most important factors in controlling the liquid crystallinity of the resulting copolyesters.

Introduction

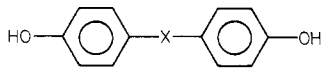
One of the most interesting recent developments in polymer chemistry is the observation of liquid crystallinity in aromatic polyesters and polyamides. For the aromatic polyamides, liquid crystallinity is observed in solutions of the polymers in specific solvents and can be referred to as a lyotropic behavior.[1-4] In contrast, the aromatic polyesters show thermotropic behavior because liquid crystallinity occurs in the melt within a specific temperature range.[5-8] In both cases the liquid crystallinity is of the nematic type, indicating that the rodlike polymer chains exist in an approximately parallel array but not lined up end-to-end. That is, there is a two-dimensional but not a three-dimensional order in the liquid crystalline phase and the placement of the mesogenic unit occurs randomly within the parallel array of molecules within this phase.

These types of polymers offer great potential in the combination of ease of processability with superior mechanical properties of strength and stiffness. However, very little information has been reported in the literature on the relationship between polymer structure and properties in such systems. Toward this end, a systematic investigation is being carried out in this laboratory on the effect of variations in composition of aromatic copolyesters on their liquid crystalline behavior and on their resulting rheological and mechanical properties. The specific systems to be discussed in this report are based on copolyesters of either chlorohydroquinone, CHQ, or methylhydroquinone, MHQ, with terephthalic acid, TPA, both of which are known to form nematic melts.[7] The copolymers studied contained a series of bisphenols which were selected to determine the effect of copolymer structure and composition on the thermotropic behavior. The bisphenols examined for this purpose are shown in Chart I. As shown in the chart, resorcinol was also included in addition to the para-substituted bisphenols. Some preliminary results of the present study have already been described.[9]

Results and Discussion

Synthesis and General Properties of Poly(chloro-*p*-phenylene terephthalate) and Copolyesters Containing Bisphenol Units. A series of aromatic copolyesters having chloro-*p*-phenylene terephthalate (I, R = Cl) and various bisphenol terephthalate (II) units as described in Chart I was synthesized in a range of comonomer compositions varying, in general, from 10 to 70 mol % of the

Chart I



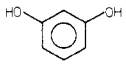
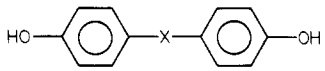
X	symbol	trivial name
none	BP	bisphenol
$C(CH_3)_2$	BPA	bisphenol A
CH_2	BPM	bisphenol methane
O	ODP	oxydiphenol
S	TDP	thiodiphenol
SO_2	SDP	sulfonyldiphenol
CO	DPB	dihydroxybenzophenone
	RES	resorcinol

Table I
Types and Amounts of Bisphenol Monomers Used To Prepare Aromatic Copolyesters



X	abbreviation	composition range, mol %
$C(CH_3)_2$	BPA [a]	0–50
CH_2	BPM [b]	30–70
O	ODP [c]	30–70
S	TDP [d]	30–60
SO_2	SDP [e]	15–60
none	BP [f]	30–70
	RES [g]	15–70

[a] Bisphenol A. [b] Bis(4-hydroxyphenyl)methane. [c] 4,4′-Oxydiphenol. [d] 4,4′-Thiodiphenol. [e] 4,4′-Sulfonyldiphenol. [f] Biphenol. [g] Resorcinol.

Table II
Synthesis and Properties of CHQ/BPA Copolyesters

monomers, mol %	yield,	polymer Cl content, wt %		η_{inh}, [a]	mp,	stir
CHQ/BPA	wt %	calcd	found	dL/g	°C	opalescence
100/0	97.6	12.9	12.9	0.384	340	very strong
90/10	98.9	11.3	11.5	0.453	347	very strong
70/30	92.9	8.30	8.40	0.638	336	weak
60/40	93.0	6.92	7.06	0.566		very weak
50/50	92.3	5.61	5.67	0.584		none

[a] Measured for solutions in *p*-chlorophenol at 45 °C, except for the first polymer, which was measured in trifluoromethanesulfonic acid at 30 °C.

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Table III
Synthesis and Properties of CHQ/BPM Copolyesters

monomers, mol % CHQ/BPM	yield, wt %	η_{inh},[a] dL/g	mp, °C	stir opalescence
70/30	98.3	0.630	304	very strong
50/50	97.1	0.407	304	strong
40/60	92.5	0.433	296	strong
30/70	96.7	0.718		none

[a] Measured for solutions in *p*-chlorophenol at 45 °C.

Table IV
Synthesis and Properties of CHQ/ODP Copolyesters

monomers, mol % CHQ/ODP	yield, wt %	η_{inh},[a] dL/g	mp, °C	stir opalescence
70/30	95.4	0.433	298	very strong
50/50	97.8	0.484	327	strong
40/60	95.9	0.401	380	strong
30/70	94.0	0.395	389	weak

[a] Measured for solutions in *p*-chlorophenol at 45 °C.

Table V
Synthesis and Properties of CHQ/TDP Copolyesters

monomers, mol % CHQ/TDP	yield, wt %	η_{inh},[a] dL/g	mp, °C	stir opalescence
70/30	98.3	0.503	314	strong
50/50	97.2	0.709	339	strong
40/60	99.0	0.655	348	weak

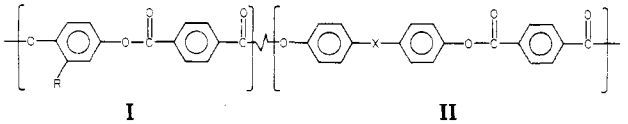
[a] Measured for solutions in *p*-chlorophenol at 45 °C.

Table VI
Synthesis and Properties of CHQ/SDP Copolyesters

monomers, mol % CHQ/SDP	yield, wt %	η_{inh},[a] dL/g	mp, °C	stir opalescence
85/15	99.8		334	very strong
70/30	98.0	0.439	342	strong
60/40	96.6	0.479	376	strong
50/50	91.9	0.315	367	weak
40/60	98.8	0.440		none

[a] Measured for solutions in *p*-chlorophenol at 45 °C.

bisphenol in 10 or 15 mol % increments; see Tables II–VIII. The overall range of compositions for each bisphenol is summarized in Table I.



I II

In general, polymer yields were high and the copolymer compositions were essentially the same as the monomer compositions, as shown in Tables II–VIII. All of the polyesters in Tables I–VIII were insoluble in the reaction medium and precipitated out as they were formed during polymerization before reaching high molecular weights. As a result, their molecular weights were not expected to be very high, and this expectation is reflected by the relatively low solution viscosity numbers obtained for all samples. Poly(chloro-*p*-phenylene terephthalate), the homopolymer from chlorohydroquinone and terephthalic acid of Table II, which had an inherent viscosity as measured in trifluoromethanesulfonic acid of 0.382 dL/g, could not be characterized for molecular weight by light scattering methods so it must have had a molecular weight well below 10 000, but no absolute value is as yet available.

Table VII
Synthesis and Properties of CHQ/BP Copolyesters

monomers, mol % CHQ/BP	yield, wt %	η_{inh},[a] dL/g	mp, °C	stir opalescence
70/30	99.3	0.107	340	strong
50/50	99.1	0.163	354	strong
30/70	99.3	0.224	390	strong

[a] Measured for solutions in trifluoromethanesulfonic acid at 30 °C; it is possible that these polymers underwent hydrolysis during characterization.

Table VIII
Synthesis and Properties of CHQ/RES Copolyesters

monomers, mol % CHQ/RES	yield, wt %	η_{inh},[a] dL/g	mp, °C	stir opalescence
85/15	97.7		334	very strong
70/30	98.0	0.363	330	very strong
50/50	98.2	0.422		strong
40/60	99.4	0.476		weak
30/70	99.4	0.390	337	none

[a] Measured for solutions in *p*-chlorophenol at 45 °C.

The melting points of the copolymers as determined by DSC were usually much less well defined than those of the homopolymers with broad and small melting endotherms, especially for the compositions containing from 40 to 60 mol % of the bisphenol comonomers. This result is understandable because these copolyesters would be expected either to have low degrees of crystallinity or to be completely amorphous. The exceptions were the CHQ/TDP copolymers of Table V, which showed sharp and well-defined melting behaviors by DSC analysis even in this composition range. The melting point of 340 °C reported in Table II for the CHQ homopolymer may be depressed because the polymer was apparently of quite low molecular weight. This polymer showed a very broad and shallow endotherm extending from about 360 °C to the upper limit for the DSC analysis of 400 °C, which is presumably associated with the transition from the liquid crystal state to the isotropic melt, that is, with the clearing temperature.

Copolymerization with small amounts of the bisphenol monomers initially depressed the melting points as expected, but at higher compositions the melting points either increased or continued to decrease, depending on the type of comonomer. In the range of compositional variations of the present study, the CHQ/BP and CHQ/ODP copolyesters were examples of the former type of copolymers while the CHQ/BPM copolymers were of the latter type. All the melting temperatures reported in the table were obtained on unannealed samples of the as-prepared polymers.

All copolymers containing 85 mol % or more of the chlorohydroquinone units and all of the CHQ/BP copolymers of Table VII were soluble at room temperature in trifluoromethanesulfonic acid, and all of those containing lower amounts of chlorohydroquinone units were soluble in *p*-chlorophenol. The polymer solutions in trifluoromethanesulfonic acid had colors ranging from light green to brown and the colors deepened with time. Because of the extremely high acidity of this acid,[10] it is likely that protonation and even degradation could be responsible for these colored solutions. The solution viscosities

Table IX
Synthesis and Properties of MHQ/BPA Copolyesters

monomers, mol % MHQ/BPA	yield, wt %	η_{inh},[a] dL/g	mp, °C	stir opalescence
100/0	96.2		371	very strong
85/15	95.9	0.491	369	strong
70/30	96.4	0.604		very weak
50/50	92.7	0.496		none

[a] Measured for solutions in 60/40 phenol/tetrachloroethane (w/w) at 30 °C.

Table X
Synthesis and Properties of 50/50 MHQ/Bisphenol Copolyesters

bisphenol	yield, wt %	η_{inh},[a] dL/g	mp, °C	stir opalescence
BPA	92.7	0.496		none
BPM	98.5	0.670	289	strong
ODP	92.8	0.524	350	strong
TDP	88.0	0.410	334	strong
SDP	94.3	0.535	354	weak
DBP[b]	94.3	0.438	399	strong
BP	98.6			strong

[a] Measured for solutions in *p*-chlorophenol at 45 °C except for the BPA copolyester, which was measured for a solution in 60/40 (w/w) phenol/tetrachloroethane mixture at 30 °C. [b] 4,4'-Dihydroxybenzophenone; X is CO.

of the BP copolymers of Table VII were much lower than those of the other copolyesters. In most cases, because of slow rates of dissolution, at least 20 h of contact time between the solvent and the polymer was required before viscosity measurements could be made and, in these strong acid solvents, hydrolytic degradation of the polymers could have occurred to lower their molecular weights.

Synthesis and General Properties of Copolyesters Derived from Methylhydroquinone and Bisphenols. A second series of copolyesters was prepared based on methylhydroquinone (MHQ, R = CH_3 in I) instead of chlorohydroquinone with the results shown in Tables IX and X. Poly(methyl-*p*-phenylene terephthalate) had a higher melting point, 371 °C, than that of the chlorohydroquinone polymer, 340 °C. As can be seen from the data in Table IX, the copolymerization of MHQ with BPA (for example, note the copolymer of 85/15 mole ratio) did not depress the melting temperature of the polyester even though the degree of crystallinity was apparently drastically reduced. However, the homopolymer melting point may well have been abnormally low because the molecular weight of this polymer was apparently quite low. Unlike all other copolyesters investigated in this study, at the 70/30 mole ratio, the MHQ copolyesters with BPA did not show a melting endotherm and it appeared that the crystallinity was completely destroyed. These copolyesters showed better solubility than CHQ copolymers and could be dissolved in a 60/40 (w/w) phenol/tetrachloroethane mixture as well as in *p*-chlorophenol. The copolymer prepared from an equimolar mixture of MHQ and BPA was fairly soluble even in tetrachloroethane at room temperature.

A series of copolyesters was prepared from equimolar amounts of MHQ with most of the bisphenols investigated in the series of CHQ copolyesters, with the results summarized in Table X. In this series, polymer yields were high, ranging from 88 to 98.5%, and the inherent viscosity numbers were in the range 0.4–0.67 dL/g. The melting endotherms observed on the DSC thermograms were rather broad for all of these copolymers with the exception of those from DBP and from TDP. In this series BPM seemed to be most effective in lowering the melting points of the resulting copolyesters. This result can probably be attributed to the combination of the low polarity and the flexible nature of the methylene substituent between the two phenolic rings. The 50/50 BPA copolymer did not show a melting endotherm in the DSC thermogram, while the 50/50 BP copolymer of Table X showed an extremely broad melting endotherm, and the melting point of this copolymer could not be properly defined.

All of the copolymers in Table X, except the BP copolyester, were completely soluble in *p*-chlorophenol, but they were only partially soluble in the 60/40 phenol/tetrachloroethane mixture. The BP copolymer was soluble in trifluoromethanesulfonic acid.

Anisotropic Liquid Crystal Polymer Melts. Thermotropic liquid crystalline phases have turbid melts and exhibit anisotropic properties, such as birefringence and light scattering.[11-14] A particular characteristic is the observation of stir opalescence of these anisotropic melts. The polyesters prepared in this investigation were examined visually for the occurrence of stir opalescence in the melts.

From observation on stir opalescence of polymer melts, attempts were made to qualitatively describe the intensity for each copolymer composition as reported in the tables. With the exception of the BP copolymers, all of the copolyesters showed a gradual reduction in the intensity of stir opalescence as the content of the bisphenol comonomer was increased. Copolymerization with all of these bisphenols markedly decreased the abilities of the polymers to form into anisotropic liquid crystal states. Another important observation made was that some of the polymers, for example, the 60/40 CHQ/RES and 40/60 CHQ/RES copolyesters, in Table VIII, the 70/30 MHQ/BPA copolyester in Table IX, and the 50/50 MHQ/BP copolyester in Table X, all of which showed essentially no crystalline melting transitions on DSC and presumably are mainly amorphous in nature, exhibited stir opalescence. This observation indicated that even apparently amorphous linear polyesters can form liquid crystal states above their glass transition temperatures if the structure of the polymers favors the parallel alignment of the polymer chains in the melt. The liquid crystal states of these polyesters could easily be quenched and supercooled to room temperature.

Ringsdorf and co-workers[15] recently observed a similar phenomenon for liquid crystalline polymers having polysiloxane flexible spacers in the main chain. These polymers also underwent a phase transition from the glassy state directly to the liquid crystal state at their softening points.

Because the melting temperatures of the polyesters of the present study were fairly high, microscopic and small-angle light scattering studies were conducted at a room temperature on polymer films prepared by quenching their melts at a temperature of about 40 °C above the melting point with ice–water. As seen in the photomicrographs of Figure 1, all of the liquid crystalline CHQ/BPA copolyester melts showed a marble texture (compare parts A–C of Figure 1),[16] and the 60/40 CHQ/BPA copolyester of Figure 1 showed only a very limited degree of birefringence with large areas of an apparently isotropic phase as indicated by the dark areas in the microphotograph. The 50/50 CHQ/BPA copolyester revealed essentially no anisotropy and did not transmit any cross-polarized light. In these samples, the occurrence of a homeotropic alignment for the 60/40 CHQ/BPA and

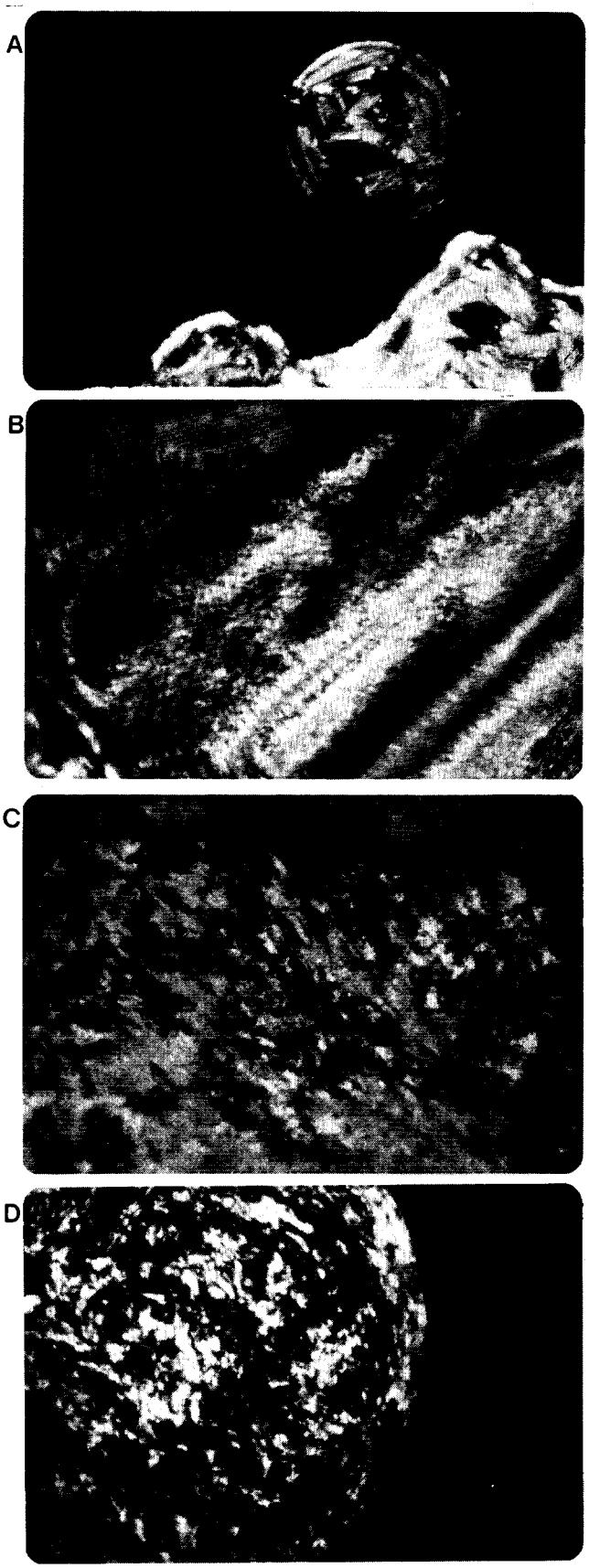


Figure 1. Photomicrographs of the quenched melts of CHQ/BPA copolyesters (photograph spans a sample length of 440 μm): (A) photomicrograph of poly(chloro-*p*-phenylene terephthalate) (magnification ×320); (B) photomicrograph of 90/10 CHQ/BPA copolyester (magnification ×320); (C) photomicrograph of 70/30 CHQ/BPA copolyester (magnification ×320); (D) photomicrograph of 60/40 CHQ/BPA copolyester (magnification ×320).

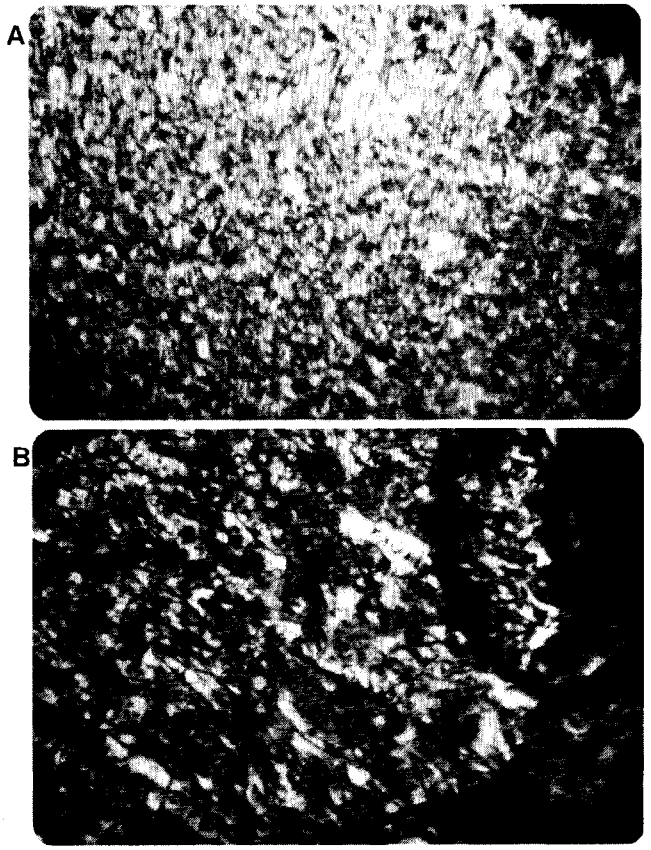


Figure 2. Photomicrographs of the quenched melts of 70/30 CHQ/ODP and 70/30 CHQ/BP copolyesters (photograph spans a sample length of 440 μm): (A) photomicrograph of 70/30 CHQ/ODP copolyester (magnification ×320); (B) photomicrograph of 70/30 CHQ/BP copolyester (magnification ×320).

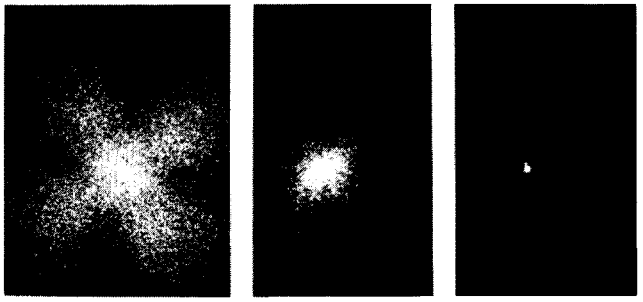


Figure 3. Small-angle light (H_v) scattering patterns of CHQ/BPA copolyesters.

50/50 CHQ/BPA copolymers, resulting in darkness under cross polarizers, is very unlikely. The observations are in complete agreement with the observed stir opalescence properties of these polymers as described above. The same comparison was true for all of the copolyesters investigated.

Figure 2 shows the photomicrographs of two other copolymers which are characterized by a threaded schlieren texture, a characteristic optical texture of nematic mesophase.[16]

Small-angle light scattering behavior of polymer films is also used to obtain information on the morphological structure of polymers in the solid state.[17,18] Because it is known that H_v scattering with crossed polars is influenced by structural anisotropy and V_v scattering with parallel polars by the density fluctuation as well as structural anisotropy,[17] only H_v scattering characteristics of the polymers were measured. The scattering patterns of some of

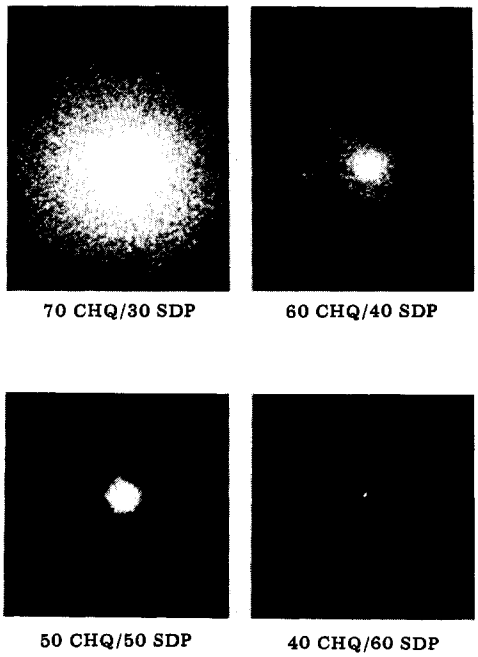


Figure 4. Small-angle light (H_v) scattering patterns of CHQ/SDP copolyesters.

the polymers are shown in Figures 3 and 4. It can clearly be seen from these photographs that the intensity of the scattered light steadily decreased with the content of the nonlinear bisphenol units in the copolyesters and that it finally became negligible or completely vanished for the compositions which are believed to form only isotropic, nonliquid crystal amorphous states. These observations are consistent with the results obtained from the microscopy study and from examination of their stir opalescence. A ±45° crossed, four-leaf clover shape for the scattering pattern was observed only for the homopolymer derived from CHQ, while circularly symmetric and azimuthally independent scattering patterns were obtained for all of the other liquid crystal compositions. This result suggests that the scattering elements of these copolyesters are generally spherical in shape and have random orientation correlations. In contrast, the homopolymer from CHQ apparently had a superstructure consisting of rigid-rod assemblies.

The small-angle light scattering characteristic of various liquid states of many low molecular weight compounds and of some polymers have been reported.[19-21] Even though theoretical interpretation of the scattering phenomena by the liquid crystal mesophases requires much more study, this method certainly provides very useful information when the size of the anisotropic domains is in the range of the wavelength of visible light of about 1000–10 000 Å. As demonstrated by us[22] and others[21], this method could be used also to follow directly the phase transition from the liquid crystal state to the isotropic state, provided that the transition temperature is not too high and is below the decomposition temperature of the polymers. For the present series of polyesters, however, the transitions from the mesophase to the isotropic phase could not be followed by this method because the polymers underwent thermal decomposition before the transition to the isotropic melt.

The wide-angle X-ray diffraction patterns of the liquid crystal state (quenched melt films) of some of the polymers examined were basically the same as those expected for nematic states.[23] As shown in Figure 5, the diffraction pattern of the polymer melt of the 70/30 CHQ/ODP copolyester of Table IV, exhibited a broad and weak inner

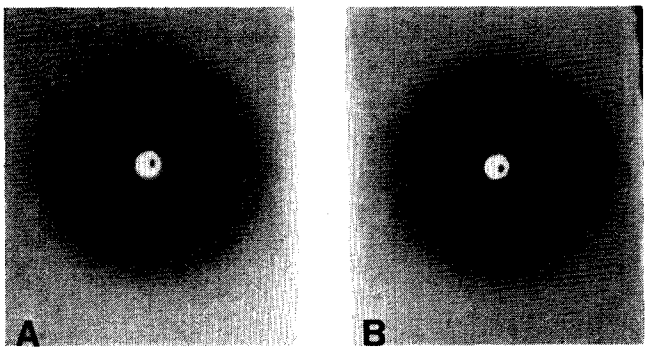


Figure 5. Wide-angle X-ray diffraction patterns of 70/30 CHQ/ODP copolyester: (A) diffraction by the original sample; (B) diffraction by the quenched sample.

ring and a stronger diffuse ring at a larger angle (2θ = 20.8°). The interplanar distance between parallel polymer chains in the nematic state as deduced from this value of 2θ with the De Vries modification[23,24] of the Bragg equation was 4.8Å. Other liquid crystal compositions prepared in this investigation, for example, the CHQ/BPA copolyesters, also showed interplanar spacings of approximately 4.7–5.0 Å. In general, inclusion of higher amounts of nonlinear bisphenol comonomers tended to increase the interplanar distance. Further X-ray studies of these polymers are in progress.

The melt viscosity of a liquid crystal melt is known to be, in general, much lower than that of an isotropic melt for polymers of the same molecular weight. In the present work, the observation of stir opalescence of polymer melts between two microscope cover glasses on a Fisher-Johns melting point apparatus permitted at least a highly qualitative conclusion that the liquid crystal melts were indeed much less viscous than the isotropic melts of nonliquid crystalline polymers, and movement of the top microscope cover glass was much easier with the liquid crystal melts than with the isotropic melts. Further study on the melt rheology of these polymers in relation to their structure and composition, which is presently in progress in this laboratory, is expected to give a more detailed picture on the relationship between melt behavior and polymer structure.

Dependence of Liquid Crystallinity of Linear Aromatic Polyesters on Their Structure. By considering all the characterization results reported here for chlorohydroquinone copolymers, we can arrive at some semiquantitative conclusions about the maximum or threshold amount of each of the bisphenol comonomers which can be incorporated into the copolymers without complete destruction of the liquid crystal nature of the resulting copolymers. With the exception of the biphenol copolymers (X is a direct covalent bond), all of the copolymers consisted of random arrangements of linear chloro-*p*-phenylene terephthalate units (I) with nonlinear ester units (II) derived from the bisphenols and terephthalic acid.

The differences in the degree of nonlinearity or bending caused by the presence of the middle substituents, X, between the two phenolic rings of the bisphenol monomers were all within about a 5° angle, which indicates that the degree of molecular bending caused by these substituents was approximately the same. The bond angles around the center atoms of the substituents ranged from about 105 to 110°. The differences in relative sizes of the substituents, however, were much greater, and it is to be expected that the larger group (e.g., $C(CH_3)_2$ and SO_2) caused increased separation of the parallel polymer chains to destabilize the nematic mesophase.[9,25] This expectation was

Table XI
Maximum Amount of Each Bisphenol Which Could Be Copolymerized without Complete Destruction of the Liquid Crystallinity of the CHQ Copolyester

bisphenol	max amount, mol %	bisphenol	max amount, mol %
BPA	40	RES	60
SDP	50	ODP	70
BPM	60	BP	100
TDP	60		

borne out by the observations made in the present study as summarized in Table XI, which clearly shows that the greater the bulkiness of the middle substituent in the bisphenol unit, the lower the threshold comonomer amount which could be accommodated in the copolymer without completely losing the liquid crystalline characteristics.

The copolymers of CHQ and RES were unique in that the resorcinol unit does not have a middle substituent, as in bisphenols, and is able to maintain the rigidity of the polymer chain, but its presence induces a bend of 120° along the backbone of the polymer chains, destroying the linearity. Again, this nonlinearity is expected to reduce the parallel association of the polymer chains in the nematic state and, thereby, to decrease the stability of mesophase. Copolyesters of MHQ/BPA (Table IX) and of MHQ with other bisphenols (Table X) showed a similar structural dependence of their liquid crystallinity on the type and amount of the bisphenols copolymerized.

The stereogeometry or space-filling characteristics of polymer molecules and the bulkiness of substituents are considered to be the two most important factors in controlling the liquid crystalline characteristics of the thermotropic, liquid crystalline, aromatic polyesters investigated here. The electronic or polar effects of the substituents on the liquid crystalline properties were not as clear as the steric effects and seemed to be relatively minor in comparison.

McFarlane and co-workers[6] studied the thermotropic liquid crystal properties of polyesters based on *p*-oxybenzoate-modified PET. They also incorporated into their polymers various nonlinear bisphenols, such as BPA and SDP, as well as nonlinear dicarboxylic acid, such as isophthalic acid. They found that the inclusion of 30 mol % of either BPA or SDP could completely destroy the liquid crystallinity of the base polymer. Replacement of the linear *p*-oxybenzoate units with the equivalent nonlinear *m*-oxybenzoate units (which impart a bending angle of 120° to the backbone) also leads to nonliquid crystalline or isotropic compositions. These observations were also attributed to the changes in geometry of the polymer chains caused by the presence of the nonlinear comonomer units. It is to be expected that the liquid crystallinity of *p*-oxybenzoate-modified PET would be destroyed more easily by the presence of small amounts of nonlinear bisphenols than for the aromatic polyesters of the present study because *p*-oxybenzoate-modified PET has nonmesogenic ethylene glycol units, which can also disrupt the mesophase.

Conclusions

It has been demonstrated that the thermotropic liquid crystalline properties of the aromatic polyesters derived from terephthalic acid and either methylhydroquinone or chlorohydroquinone copolymerized with varying amounts of different bisphenols were greatly dependent upon both the structure and the amount of the nonlinear comonomer units or "spacers". The nonlinear bisphenol spacers containing large or bulky central substituents between the two phenolic rings were found to be more effective in destroying the liquid crystal properties of the resulting copolyesters than those with smaller substituents. Hence, it was concluded that the geometric and steric effects imparted to the polymer chain backbones by the comonomers were the most important controlling factors affecting the liquid crystallinity of the aromatic copolyesters.

Experimental Section

Preparation of Polyesters. All of the polyesters were prepared at room temperature by the reaction of an aromatic diol mixture with terephthaloyl chloride in a mixture of 1,1,2,2-tetrachloroethane and pyridine. Detailed procedures were described in an earlier paper.[9]

Characterization of Polymers. Inherent viscosities of polymers were determined with a Cannon-Ubbelhode type viscometer. The thermal properties were measured under a nitrogen atmosphere on a Perkin-Elmer DSC-1B with a heating rate of 20 °C/min. The temperature of endotherm maximum was taken as the melting point of the polymer.

Visual observation of stir opalescence of polymer melts was made as follows: a small amount of the polymer sample was placed between two microscope cover glasses on a Fisher-Johns melting point apparatus and heated rapidly to the melting temperature, which had been predetermined by DSC. The heating rate was then reduced to about 20 °C/min, and the top cover glass was moved back and forth with a microspatula while the occurrence of stir opalescence was visually observed with a magnifying glass attached to the apparatus. Continuous observations were made up to the decomposition temperature of polymers.

For microscopy and small-angle light scattering studies, a small amount of the polymer sample was placed between two microscope cover glasses on a Fisher-Johns apparatus, which had been preheated to a temperature of 40–50 °C above the polymer melting point. After the sample melted completely, the melt was rapidly quenched in an ice–water bath and the sample was stored at low temperature. The thickness of the quenched melt films was generally in the range 10–25 mμ. The optical texture of the samples was studied by using a microscope (Leitz, Ortholux model) equipped with a pair of crossed polarizers. The small-angle light scattering characteristics of the samples were examined by a He–Ne (λ 6328 Å) laser fitted with a red filter on an optical bench with a pair of crossed polarizers. The scattering pattern was photographed with Polaroid Type 52 or 57 films. A 1-mm pinhole was placed behind the sample. The sample-to-film distance was 32–35 cm.

Samples for X-ray analysis were prepared in a different manner. The polymer powder (about 0.5 g) was spread inside a boat made of aluminum foil coated with poly(tetrafluoroethylene) (du Pont Teflon) and the boat was floated on a salt bath, which was preheated to about 50 °C above the melting temperature of the polymer. When the sample was completely melted, the boat was removed from the bath while liquid nitrogen was poured into it. The quenched polymer was pressed at a room temperature into a thin (~0.5 mm) round pellet, which was used for X-ray analysis at room temperature. The original polymer powders were also pressed into thin pellets for X-ray analysis. The pelletized samples were affixed to the sample holder in an X-ray machine for a 16–30-h exposure.

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Mass Transfer of Macromolecules in Steric Exclusion Chromatography. 1. Diffusional Transport in the Pores of Steric Exclusion Chromatography Materials

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ABSTRACT: The analysis of peak broadening as a function of flow rate in steric exclusion chromatography (SEC) of polymer samples gives information about transport processes of macromolecules in the pores of the stationary phase. Two different chromatographic materials—VITX glass and TSK polystyrene—were in studying the hindrance to diffusion and its dependence on porosity, pore size, and partition coefficient. For both stationary phase materials the hindrance to diffusion was considerably greater than expected, as shown by obstruction factor values around 0.2. Furthermore, the obstruction factor was found to be independent of the partition coefficient K in the range $0.35 < K < 1$. An increase of the obstruction factors calculated from peak broadening is found at lower values of K for the polystyrene column.

1. Introduction

It now seems generally accepted that the separation effect in gel permeation chromatography (GPC) is mainly based on steric exclusion of molecules from part of the internal pore volume. As in any other chromatographic process the separation can be described by equilibrium thermodynamics and—with the exception of some limiting cases—not by hydrodynamics. The coefficient K of the partition of molecules between the internal pore volume, V_i, and the interstitial volume, V_0, is given by the ratio of the configuration integral of the attainable positions in the pores and the integral in the same volume of free solution.[1,2] The separation effect of this type of chromatography—usually called GPC—is better described by the terminology "steric exclusion chromatography" (SEC).

Some effects however remain to be investigated concerning the behavior of molecules in SEC: (i) the possible influence of enthalpy effects (adsorption and nonideal behavior of flexible macromolecules), (ii) the diffusional transport of molecules in the internal pores, especially in the separation range, i.e., under the influence of steric hindrance, (iii) the possibility of convective transport of molecules in the internal pores and the resulting change in the separation mechanism, and (iv) the behavior of macromolecules in the interstitial volume if their radius is no longer small compared to the radius of the external pores.

In this series of papers theoretical considerations and experimental results concerning the last three topics are presented. The present paper is concerned with the diffusional transport of molecules in the internal pores. Steric exclusion from part of the internal volume might lead to a hindrance of the transport. Even if no exclusion takes place, the diffusion coefficient in porous materials is lowered compared with that in the free solution. While having no influence on the distribution coefficient, such effects deteriorate the mass transfer and, as a result, increase the peak broadening.

Diffusional transport in internal pores influences peak broadening in most versions of chromatography. Due to their low diffusion coefficient, macromolecules are especially suited for the investigation of diffusional mass transfer.

2. Theoretical and Experimental Background

The SEC of macromolecules normally operates in a range of velocities where longitudinal dispersion can be neglected and the broadening in the interstitial volume is independent of the flow rate ("eddy dispersion").

The broadening due to mass transfer in the stationary phase is proportional to the fow rate, $\dot{V}$. Therefore, in the

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