

Syntheses and Properties of New Poly(amide-imide)s Based on 1,4-Bis(4-aminophenoxy)naphthalene and Various Diimide-Diacids

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Received 18 May 1999; accepted 14 October 1999

ABSTRACT: A series of new alternative poly(amide-imide)s (PAIs, **III_{a-j}**) was synthesized by the direct polycondensation of 1,4-bis(4-aminophenoxy)naphthalene (**1,4-BAPON**) with various aromatic diimide-diacids. These polymers were obtained in quantitative yields with inherent viscosities of 0.71–1.03 dL/g. Except for **III_a**, most of the polymers were soluble in aprotic polar solvents such as NMP, DMAc, DMF, and DMSO and could be solution-cast into transparent, flexible, and tough films. The glass transition temperatures of these PAIs were in the range of 235–280°C. Thermogravimetric analyses established that these polymers were fairly stable up to 450°C, and 10% weight loss temperatures were recorded in the range of 520–569°C under nitrogen and 506–566°C under an air atmosphere. Compared with the PAIs with the 1,4-bis(4-aminophenoxy)benzene structure (series **IV**), the solubility of series **III** was better than that of series **IV**. Series **III** also exhibited lower crystallinity and better processability than those of series **IV**. © 2000 John Wiley & Sons, Inc. *J Appl Polym Sci* 77: 217–225, 2000

Key words: 1,4-bis(4-aminophenoxy)naphthalene; aromatic poly(amide-imide); direct polycondensation

INTRODUCTION

Aromatic poly(amide-imide)s (PAIs) are useful high-performance materials that exhibit better processing characteristics when compared with polyimides of analogous structures.^{1,2} Conventionally, PAIs can be prepared in several ways, starting from trimellitic anhydride (TMA): First, two-step polycondensation from acyl chloride of TMA with aromatic diamines involving polycondensation and subsequent cyclodehydration³; second, low-temperature-solution polycondensation

of a TMA-derived imide ring-performed diacyl chlorides and aromatic diamines³; and, third, polycondensation of a TMA or TMA-derived imide ring-containing dicarboxylic acids with diisocyanates.^{5–7} Recently, we successfully applied a direct phosphorylation reaction⁸ to synthesize high molecular weight PAIs by direct polycondensation of imide-containing dicarboxylic acids with aromatic diamines.^{9–14} This direct polycondensation route avoids using moisture-sensitive acyl chloride or isocyanates and provides significant advantages in the laboratory preparation of PAIs.

Acceding to recent publications,^{15–19} the introduction of a naphthalene ring into the polymer backbone has some advantages for structure modification such as increasing the solubility of polymers, lowering the phase-transfer temperature,

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Contract grant sponsor: Tatung University; contract grant number: B88-1401-01.

Journal of Applied Polymer Science, Vol. 77, 217–225 (2000)
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Table I Reaction Conditions for the Preparation of PAIs

Polymer	Amount of Reagents			η_{inh}^a (dL/g)
	NMP (mL)	CaCl ₂ (g)	Py (mL)	
III _a	5.5	0.55	1.5	0.73 ^b
III _b	4.0	0.41	1.2	0.86
III _c	4.0	0.35	1.1	0.71
III _d	5.0	0.46	1.2	0.78
III _e	5.0	0.45	1.2	0.75
III _f	4.0	0.35	1.0	0.83
III _g	4.5	0.42	1.0	0.87
III _h	3.5 + 1	0.32	0.8	1.03
III _i	3.5	0.33	0.8	0.76
III _j	4.0	0.32	1.0	0.93
IV _a	6.0	0.65	1.5	0.11 ^c
IV _b	5.6 + 1	0.5	1.2	0.87
IV _c	6.0 + 0.5	0.4	1.2	1.13
IV _d	5.0 + 1.5	0.5 + 0.2	1.2	0.45 ^b
IV _e	6.0 + 1.0	0.6 + 0.1	1.2	0.71 ^b
IV _f	5.0 + 3.5	0.5	1.2	0.79 ^b
IV _g	6.0	0.7	1.5	0.14 ^c
IV _h	6.0 + 2	0.7	1.5	0.19 ^c
IV _i	5.0 + 1.5	0.5	1.2	0.84 ^b
IV _j	5.0	0.45	1.2	0.95 ^b

In each polymerization, 1 mmol of monomer and 0.6 mL of TPP was used. Reaction temperature = 100°C; reaction time = 3 h.

^aMeasured at a polymer concentration of 0.5 g/dL in DMAc at 30°C.

^bMeasured at a polymer concentration of 0.5 g/dL in DMAc + 0.5 wt % LiCl at 30°C.

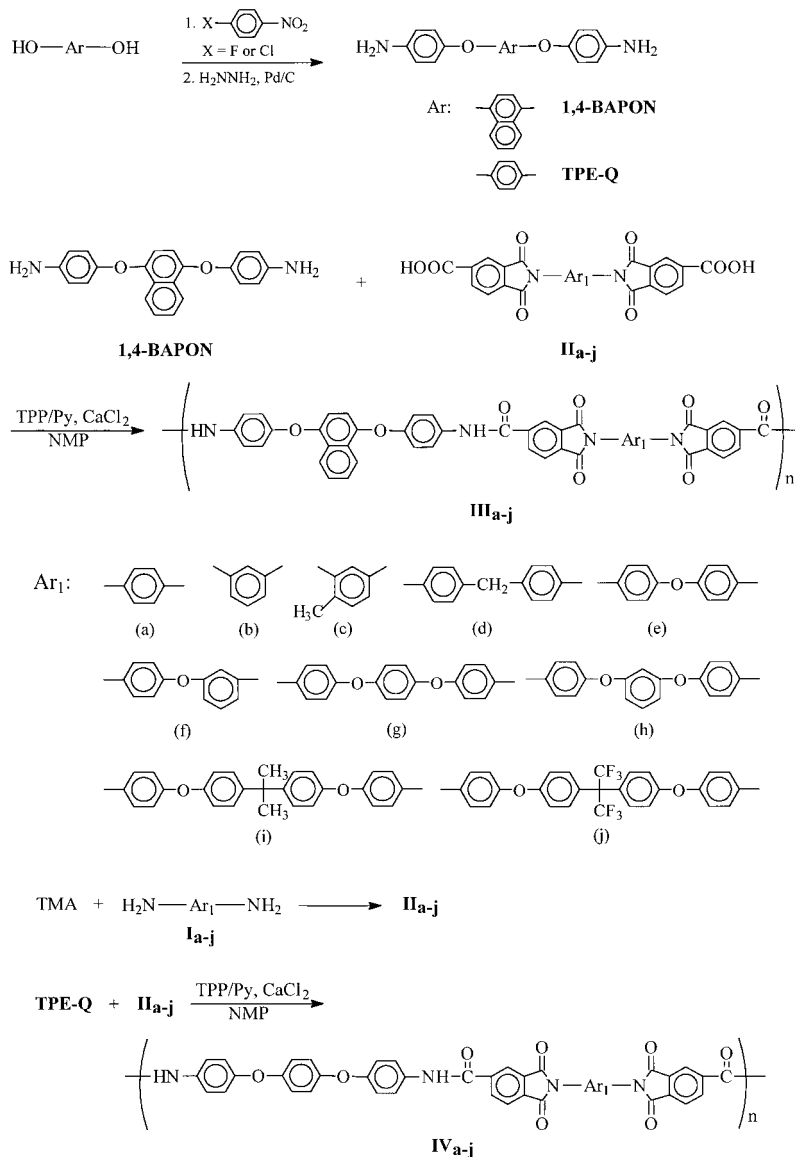
^cMeasured at a polymer concentration of 0.5 g/dL in concentrated H₂SO₄ at 30°C.

and retaining the thermal stability. 1,4-Bis(4-aminophenoxy)naphthalene (**1,4-BAPON**), containing a structure similar to 1,4-bis(4-aminophenoxy)benzene, has a substituted phenyl ring in the 2,3-position that forms an asymmetric structure in the 2,3- and 5,6-positions of the benzene ring. Because the synthesis of **1,4-BAPON** is more difficult than that of the other bis(aminophenoxy)naphthalenes,²⁰ the properties of PAIs having **1,4-BAPON** units in the main chains have not been reported. In this work, a series of new **1,4-BAPON**-containing PAIs was prepared by the direct polycondensation of **1,4-BAPON** with various diimide-diacids using triphenyl phosphite (TPP) and pyridine as a condensing agent. Physical properties of these new PAIs were reported and also compared with the PAIs (**IV_{a-j}**) derived from 1,4-bis(4-aminophenoxy)benzene (**TPE-Q**). Although the diamine **TPE-Q** is not a new monomer, the PAIs **IV_{a-j}** have not been systematically reported on concerning their preparations and physical properties.

EXPERIMENTAL

Materials

1,4-Dihydroxynaphthalene (from TCI), *p*-fluoronitrobenzene (from Janssen), 10% palladium on activated carbon (Pd/C; from Fluka), TMA (from Wako), TPP (from Fluka), and **TPE-Q** (**I_g** from TCI) were used as received. Aromatic diamines including *p*-phenylenediamine (**I_a**), *m*-phenylenediamine (**I_b**), 2,4-diaminotoluene (**I_c**), 4,4'-diaminophenyl methane (**I_d**), 4,4'-diaminophenyl ether (**I_e**), and 3,4'-diaminophenyl ether (**I_f**) were used directly as received from TCI. 1,3-Bis(4-aminophenoxy)benzene (**I_h**), 2,2-bis[4-(aminophenoxy)phenyl]propane (**I_i**), and 2,2-bis[4-(aminophenoxy)phenyl]hexafluoropropane (**I_j**) were obtained from Chriskev and used without further purification. Reagent-grade calcium chloride was dried under a vacuum at 180°C before use. *N*-Methyl-2-pyrrolidone (NMP), *N,N*-dimethylformamide (DMF), and pyridine were purified by



Scheme 1

distillation under reduced pressure over calcium hydride and stored over 4 Å molecular sieves.

Monomer Synthesis

According to the method reported in a previous article,²⁰ **1,4-BAPON** was synthesized starting from the nucleophilic displacement of 1,4-dihydroxynaphthalene and *p*-fluoronitrobenzene in the presence of potassium carbonate, giving 1,4-bis(4-nitrophenoxy)naphthalene (**1,4-BNAPON**), and followed by reduction with a hydrazine and Pd/C system (mp 113–115°C). Diimide-diacids

(**II_{a-j}**) were prepared according to a previous method^{9,10} by condensing diamines (**I_{a-j}**) with TMA followed by dehydration in a toluene–water azeotropic distillation.

Polymerization

The PAIs (series **III**) were prepared by direct polycondensation using the following general procedure: Taking **III_h** as an example, a mixture of 0.342 g (1.0 mmol) of diamine **1,4-BAPON**, 0.640 g (1.0 mmol) of diimide-diacid **II_h**, 0.32 g of calcium chloride, 3.5 mL of NMP, 0.8 mL of pyridine,

Table II Elemental Analysis of PAIs

Polymer	Formula (Molecular Weight)	Elemental Analysis (%) ^a			Moisture Intake (%) ^b	
			C	H		N
III_a	(C ₄₆ H ₂₆ N ₄ O ₈) _n (762.71) _n	Calcd	72.77	3.44	7.34	4.19
		Found	69.55	3.68	7.21	
		Corrected	72.59	3.53	7.52	
III_b	(C ₄₆ H ₂₆ N ₄ O ₈) _n (762.71) _n	Calcd	72.77	3.44	7.34	3.72
		Found	69.86	4.06	7.18	
		Corrected	72.55	3.91	7.45	
III_c	(C ₄₇ H ₂₈ N ₄ O ₈) _n (776.76) _n	Calcd	72.67	3.63	7.21	3.99
		Found	69.95	3.86	7.05	
		Corrected	72.80	3.70	7.34	
III_d	(C ₅₃ H ₃₂ N ₄ O ₈) _n (852.84) _n	Calcd	74.64	3.78	6.57	3.38
		Found	72.14	3.82	6.49	
		Corrected	74.65	3.67	6.71	
III_e	(C ₅₂ H ₃₀ N ₄ O ₉) _n (854.84) _n	Calcd	73.10	3.54	6.55	2.09
		Found	71.48	3.67	6.37	
		Corrected	73.01	3.60	6.51	
III_f	(C ₅₂ H ₃₀ N ₄ O ₉) _n (854.84) _n	Calcd	73.10	3.54	6.55	2.02
		Found	71.62	3.64	6.27	
		Corrected	73.11	3.54	6.55	
III_g	(C ₅₈ H ₃₄ N ₄ O ₁₀) _n (946.93) _n	Calcd	73.57	3.62	5.92	3.45
		Found	70.59	3.71	6.34	
		Corrected	73.10	3.58	6.55	
III_h	(C ₅₈ H ₃₄ N ₄ O ₁₀) _n (946.93) _n	Calcd	73.57	3.62	5.92	2.62
		Found	71.63	3.56	5.99	
		Corrected	73.66	3.56	5.91	
III_i	(C ₆₇ H ₄₄ N ₄ O ₁₀) _n (1065.11) _n	Calcd	75.55	4.16	5.26	2.81
		Found	73.42	4.30	5.13	
		Corrected	75.54	4.18	5.27	
III_j	(C ₆₇ H ₃₈ F ₆ N ₄ O ₁₀) _n (1173.06) _n	Calcd	68.60	3.26	4.77	2.38
		Found	66.95	3.37	4.68	
		Corrected	68.58	3.29	4.79	

^aFor C and N: corrected value = found value × (100% + moisture intake %). For H: corrected value = found value × (100% - moisture intake %).

^bMoisture intake (%) = (W - W₀)/W₀ × 100%. W is the weight of polymer sample after standing at room temperature for 3 days. W₀ is the weight of polymer sample after dried in vacuum at 100°C for 12 h.

and 0.6 mL of TPP was heated with stirring at 100°C. The polymer solution was too viscous to stir after 1 h and was diluted gradually with an additional 1 mL of NMP to maintain smooth stirring. After 3 h of stirring at 100°C, the viscous polymer solution was slowly poured into 400 mL of stirred methanol to give rise to a stringy precipitate which was washed thoroughly with methanol and hot water, collected by filtration, and dried at 100°C under a vacuum. The yield was quantitative. The inherent viscosity of polymer **III_h** was 1.03 dL g⁻¹, as measured at a concentration of 0.5 g/dL in DMAc at 30°C. Other PAIs in this series (**III_{a-j}**) were synthesized analogously.

PAIs **IV** were prepared by a similar process as above, but the diamine monomer **TPE-Q** was used to replace **1,4-BAPON**. The amounts of solvents and calcium chloride were larger to synthesize PAIs. Synthetic conditions and inherent viscosities of the obtained polymers are summarized in Table I.

Measurements

Melting points were measured in capillaries on a Yamato mp apparatus (Model MP-21) without correction. Elemental analyses were run on a Perkin-Elmer Model 2400 C, H, N analyzer. The inherent viscosities of PAIs were measured at a 0.5 g/dL concentration with a Cannon-Fenske

Table III Solubility of PAIs

Polymer	Solvent						
	DMAc	NMP	DMF	DMAc + 5% LiCl	DMSO	Py	<i>m</i> -Cresol
III _a	-	+ -	-	+	-	-	-
III _b	+	+	+	+	+ -	+	-
III _c	+	+	+	+	+	+	+
III _d	+	+	+	+	+	+	+
III _e	+	+	+	+	+ -	+	+ -
III _f	+	+	+	+	+	+	+
III _g	+	+	+	+	+	+ -	+ -
III _h	+	+	+	+	+	+	+
III _i	+	+	+	+	+	+	+
III _j	+	+	+	+	+	+	+
IV _a	-	-	-	+ -	-	-	-
IV _b	+	+	+	+	+	+	+
IV _c	+	+	+	+	+	+	+
IV _d	+	+	+	+	+	+	+
IV _e	+ -	+ -	-	+	-	-	-
IV _f	+ -	+ -	-	+	-	-	-
IV _g	-	-	-	+ -	-	-	-
IV _h	-	-	-	-	-	-	-
IV _i	+ -	+	-	+	-	-	-
IV _j	-	+	-	+	-	-	-

Solubility: (+) soluble at room temperature, (+-) partially soluble or swelling, (-) insoluble.

viscometer at 30°C. Thermogravimetric analysis (TGA) was conducted with a Rigaku thermoflex TG 8110 coupled to a Rigaku TAS-100 thermal analysis station. Experiments were carried out on 10 ± 2 -mg samples heated in flowing nitrogen or air ($50 \text{ cm}^3/\text{min}$) at a heating rate of $20^\circ\text{C}/\text{min}$. Differential scanning calorimetry (DSC) traces were performed on a Sinku-Riko DSC-7000 differential scanning calorimeter coupled to a TA 7000 thermal analyzer in flowing nitrogen ($30 \text{ cm}^3/\text{min}$) at a heating rate of $20^\circ\text{C}/\text{min}$. Wide-angle X-ray diffraction patterns were obtained on a Rigaku Geiger D-Max IIIa X-ray diffractometer, using Ni-filtered $\text{CuK}\alpha$ radiation (40 kV, 15 mA) with film specimens of about 0.1 mm in thickness. The scanning rate was $2^\circ/\text{min}$. An Instron Universal Test Model 1130 with a load cell of 5 kg was used to study the stress-strain curves of the samples. A gauge of 2 cm and a strain rate of 5 cm/min were used. Measurements were performed at room temperature with film specimens (0.5 cm wide, 6 cm long, and 0.1 mm thick), and the average of at least six individual determinations was used.

RESULTS AND DISCUSSION

Synthesis

A series of novel poly(amide-imide)s (PAIs, III_{a-j}) was synthesized by the direct polycondensation of **1,4-BAPON** with various aromatic diimide-diacids (II_{a-j}), as shown in Scheme 1. As reported recently,²⁰ the diamine **1,4-BAPON** was prepared from the displacement reaction between 1,4-dihydroxynaphthalene and *p*-fluoronitrobenzene followed by catalytic reduction. Diimide-diacids (II_{a-j}) were synthesized from the condensation of diamines (I_{a-j}) with TMA followed by dehydration. Generally, to obtain PAIs of high molecular weight in a direct polycondensation, the solubility of the polymer seems to be an important factor; although the optimum condition may vary with different kinds of monomers. Under homogeneous conditions, higher polymer concentrations and a suitable amount of salt (CaCl_2) were favorable for polymerization.

The synthesis conditions and inherent viscosities of PAIs III_{a-j} and IV_{a-j} are listed in Table I. The inherent viscosities of III_{a-j} were in the

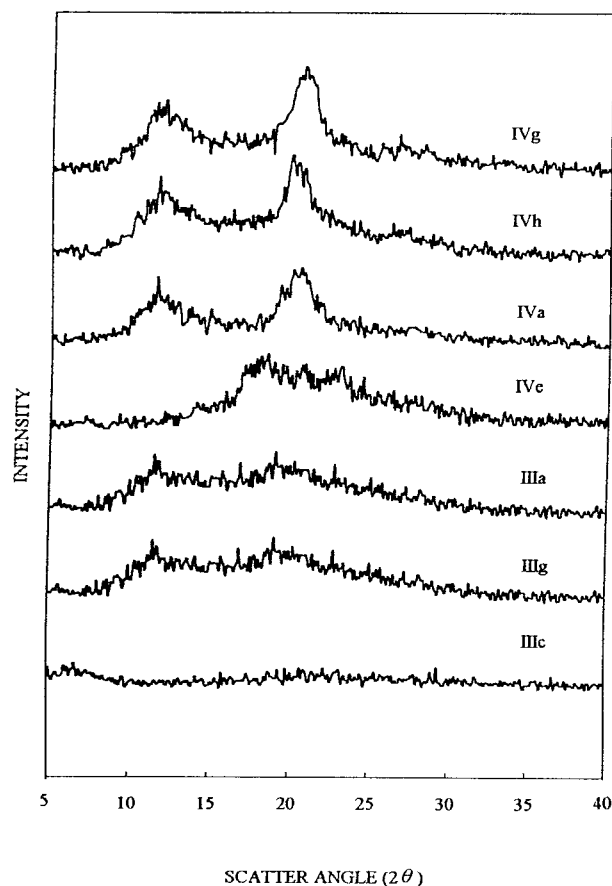


Figure 1 Wide-angle X-ray diffractograms of polymers.

range of 0.71–1.03 dL/g. In series **III**, the diamine **1,4-BAPON** exhibited good solubility in organic solvents, making reaction conditions dependent

on the kind of diimide–diacid. Larger amounts of solvents and salt were needed to prevent the precipitation from occurring and to allow the direct polycondensation reaction to process smoothly for PAIs **III**_{a,d,e} derived from rigid diimide–diacid moieties. For polymers **III**_{g,h,i} containing flexible diacid moieties, solvent and salts could be reduced to a smaller amount than those of **III**_{a,d,e}. With the polymer solution of **III**_h too viscous to stir during the reaction period, an additional 1 mL of NMP was added to maintain stirring and to provide a high molecular weight for the polymer. PAIs **IV**_{a–j}, synthesized from **TPE-Q** and aromatic diimide–diacids using a similar procedure, were prepared for physical property comparisons with series **III**. The amounts of solvent and salts needed for preparation of PAIs **IV** were larger than the corresponding polymers **III**, because the diamine monomer **TPE-Q** was more rigid than **1,4-BAPON**. Polymers **IV**_{a,g,h} precipitated during the polymerization, even though larger amounts of solvent and salt were added to the solution, so lower molecular weights of the polymer were obtained.

The results of the elemental analyses of all the PAIs are shown in Table II. The carbon values were found to be lower than the calculated values for the proposed structures in all cases. This is attributed to the hygroscopic nature of amide groups of these PAIs. The intake of water was in the range of 2.09–4.19%, which were calculated from the weight change of the vacuum-dried polymer samples after being exposed in air at room temperature. When the found values were cor-

Table IV Tensile Properties of PAIs

Polymer ^a	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation at Break (%)	Initial Modulus (GPa)
III _b	—	90	10.8	2.1
III _c	86	78	10.4	2.0
III _d	—	82	8.9	2.3
III _e	—	93	9.3	2.1
III _f	—	96	9.5	2.2
III _g	108	103	12.9	2.4
III _h	—	99	12.5	2.3
III _i	97	86	10.5	2.0
III _j	112	105	12.3	2.5
IV _b	82	81	17.0	2.4
IV _c	89	87	15.4	2.1
IV _d	—	85	10.3	2.2

^aFilms were cast from polymer solution of DMAc.

Table V Thermal Properties of PAIs

Polymer	TGA			
	DSC	Decomposition Temperature ^b (°C)		
	T_g^a (°C)	In N ₂	In Air	Wt % Residue at 800°C in N ₂
III_a	—	569	566	65.3
III_b	280	565	560	64.3
III_c	273	534	515	62.5
III_d	—	529	522	58.3
III_e	263	533	523	63.6
III_f	250	531	514	63.4
III_g	257	545	545	60.1
III_h	240	520	506	60.8
III_i	235	533	534	61.5
III_j	250	563	550	59.5
IV_a	—	534	527	62.3
IV_b	285	562	558	63.2

^aFrom the second-heating DSC traces conducted at a heating of 20°C/min in nitrogen.

^bTemperature at which a 10% weight loss was recorded by TGA at a heating rate of 20°C/min.

rected by eliminating the amount of water absorbed, the correction values were in good agreement with the calculated ones.

Properties of Polymers

The qualitative solubility of PAIs was tested in various solvents at room temperature as a concentration of approximately 1% (w/v). The results are shown in Table III. Except for **III_a**, PAIs **III** were readily soluble in polar solvents like NMP, DMAc, DMF, and DMSO. Polymer **III_b**, containing *meta*-oriented benzene in a diimide-diacid residue was easily soluble in test solvents when compared with **III_a**. On the contrary, most PAIs **IV** showed poor solubility in organic solvents. The solubility of series **III** was better than that of series **IV**, especially for the PAIs containing an ether linkage in diimide-diacid moieties such as **III_{e,f,g,h}**. This may be attributed to the introduction of the naphthalene unit into the polymer backbone, a move that reduces the polymer packing density and interchain interaction.

The crystallinity of polymers was evaluated by an X-ray diffraction measurement with scattering angles 2θ from 5°–40°, as shown in Figure 1. All polymers **III** showed amorphous characteristics and exhibited no observable reflection peak in the test range. But in series **IV**, **IV_{a,g,h}** showed crys-

talline characteristics and exhibited stronger reflection peaks. From this result, the lower crystallinity of series **III** could be confirmed when compared with the related polymers **IV**.

Table IV summarizes the tensile properties of the polymers. Most polymers afforded transparent, tough, and flexible films by casting from their DMAc solutions. The PAI films had yield strengths of 86–112 MPa, tensile strengths of 78–105 MPa, elongations at break of 8.9–12.9%, and initial moduli of 2.0–2.5 GPa. **III_{c,g,i,j}** showed yield points on their stress-strain curves, revealing the tough characters of polymer films. The films **III_{g,j}** exhibited the best tensile properties, because their tensile strengths were higher than 100 MPa and their initial moduli higher than 2.4 GPa. The tensile strengths of series **III** were higher than those of series **IV**, suggesting that the incorporation of the **1,4-BAPON** unit into the polymer chain was better for the improvement of processability than that of other related units.

The thermal stability and glass transition temperatures (T_g 's) of PAIs were evaluated by thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), respectively. The 10% decomposition temperatures (T_d 's) in air and nitrogen atmospheres and the char yields at 800°C in nitrogen are summarized in Table V. The T_d 's of PAIs **III** were recorded in

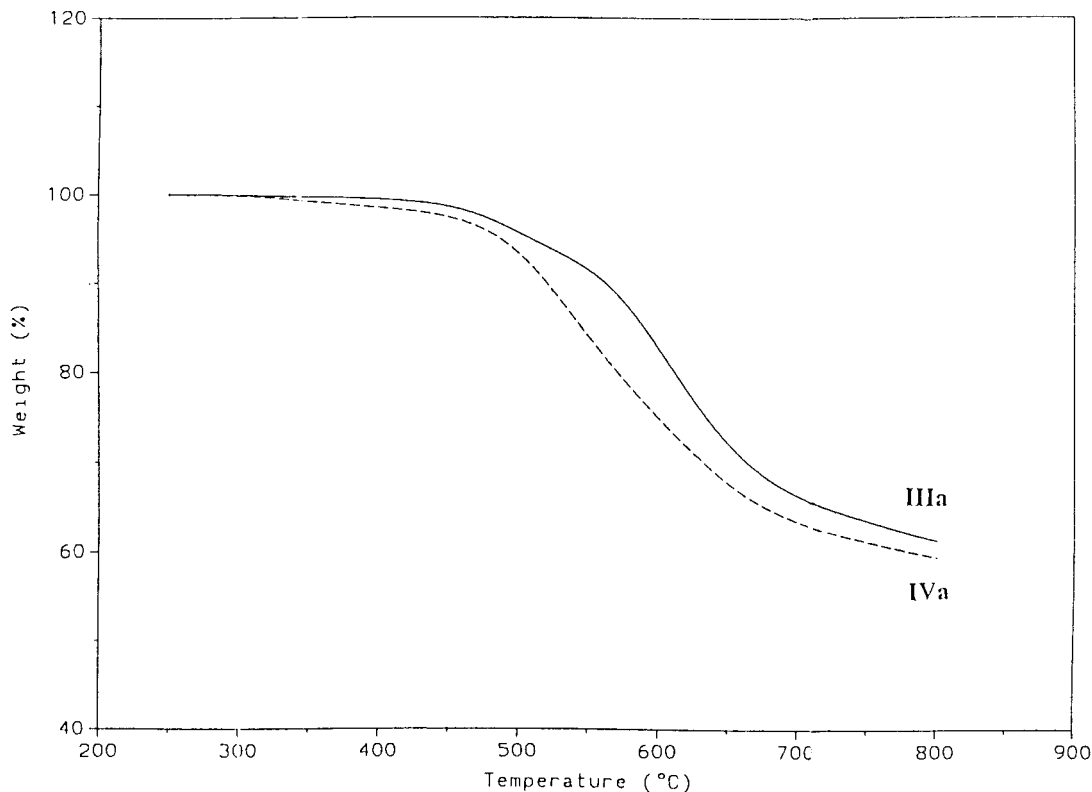


Figure 2 TGA curves of **III_a** and **IV_a** at a heating rate of 20°C/min under nitrogen.

the range of 520–569°C in nitrogen and 506–566°C in air. The PAIs **III_{a,b}** containing *p*-phenylene or *m*-phenylene units in the diimide-diacids showed the best thermal stability, due to their high aromaticity. The fluorine-containing PAI **III_j** showed better thermal stability than its nonfluoro analogous **III_i**, due to that the C—F bond of the CF₃ group is stronger than the C—H bond of the CH₃ group. Comparisons of thermal properties of related polymers **IV_{a,b}** are also shown in Table V and Figure 2. The TGA curves of PAIs **III_a** and **IV_a** showed that both of them had good thermal stability below 450°C and the *T_d* of **III_a** was 35°C higher, a characteristic that may result from the low degree of polymerization of **IV_a**.

The *T_g*'s of PAIs were recorded in the range of 235–280°C. However, no discernible *T_g* was detected for polymers **III_{a,d}** from DSC traces in the test range. Higher *T_g*'s of **III_{b,c}** in polymers **III** may be caused by the rigid structures of diimide-diacids that contain no ether linkages. Polymer **III_i** exhibits the lowest *T_g* because its diacid moiety has a flexible isopropyl group. Polymer **III_j**,

containing bulk CF₃ groups in the diacid moiety have increased steric hindrances, leading to a higher *T_g* than that of **III_i**.

CONCLUSIONS

A series of novel aromatic PAIs containing 1,4-bis-(phenoxy)naphthalene units was prepared by the direct polycondensation of 1,4-bis(aminophenoxy)naphthalene and various diimide-diacids. Most of the PAIs are characterized by good solubility in organic solvents, excellent mechanical properties, and high thermal stability. Compared with the related isomers, this series of polymers exhibits some advantages such as lower crystallinity, better solubility, and higher thermal stability.

We are grateful to the Tatung University for the support of this work (B88-1401-01).

REFERENCES

1. Polyimide: Synthesis, Characterization, and Application; Mittal, K. L., Ed.; Plenum: New York, 1984; Vols. 1 and 2.

- Feld, W. A.; Ramalingam, B.; Harris, F. W. *J Polym Sci Polym Chem Ed* 1983, 21, 319.
- Ghatge, N. D.; Shinde, B. M.; Mulik, U. P. *J Polym Sci Polym Chem Ed* 1984, 22, 3359.
- Imai, Y.; Maldar, N. N.; Kakimoto, M. *J Polym Sci Part A Polym Chem* 1989, 22, 2198.
- Jeong, H. J.; Oishi, Y.; Imai, Y.; Kakimoto, M. *J Polym Sci Part A Polym Chem* 1991, 29, 39.
- Jeong, H. J.; Imai, Y.; Kakimoto, M. *J Polym Sci Part A Polym Chem* 1991, 29, 1691.
- Imai, Y.; Maldar, N. N.; Kakimoto, M. *J Polym Sci Part A Polym Chem* 1992, 30, 1027.
- Yamasaki, N.; Kakimoto, M.; Higashi, F. *J Polym Sci Part A Polym Chem* 1975, 13, 1373.
- Yang, C. P.; Hsiao, S. H. *Makromol Chem* 1989, 190, 2119.
- Hsiao, S. H.; Yang, C. P. *Makromol Chem* 1990, 191, 155.
- Hsiao, S. H.; Yang, C. P. *J Polym Sci Part A Polym Chem* 1990, 28, 1149.
- Hsiao, S. H.; Yang, C. P. *J Polym Sci Part A Polym Chem* 1991, 29, 1175.
- Yang, C. P.; Lin, J. H.; Hsiao, S. H. *J Polym Sci Part A Polym Chem* 1991, 29, 1175.
- Yang, C. P.; Hsiao, S. H.; Lin, J. H. *J Polym Sci Part A Polym Chem* 1992, 30, 1685.
- Yang, C. P.; Chen, W. T. *Makromol Chem* 1993, 194, 3071.
- Yang, C. P.; Chen, W. T. *J Polym Sci Part A Polym Chem* 1993, 31, 3081.
- Yang, C. P.; Chen, W. T. *J Polym Sci Part A Polym Chem* 1994, 32, 453.
- Yang, C. P.; Lin, J. H. *J Polym Res* 1996, 3, 2323.
- Yang, C. P.; Hsiao, S. H.; Yang, C. C. *J Polym Sci Part A Polym Chem* 1998, 36, 919.
- Yang, C. P.; Chen, J. A. *Polym J* 1998, 30, 571.