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POLYMER DATA HANDBOOK

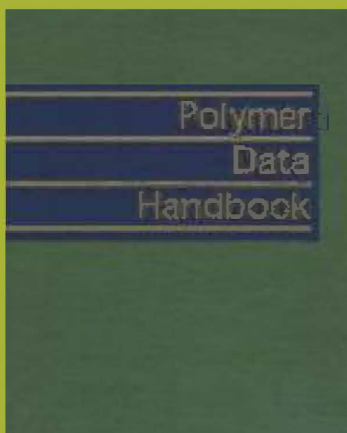
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EDITED BY JAMES E. MARK, UNIVERSITY OF CINCINNATI

PUBLISHED BY OXFORD UNIVERSITY PRESS

The online version of the *Polymer Data Handbook* includes key data on over two hundred polymers. Please note that entries are presented as PDF files and can only be read using Adobe Acrobat Reader Version 3. If you do not have the freeware reader, it can be downloaded from [Adobe in the United States](#) or [Adobe in the United Kingdom](#). Each entry opens with a citation of the contributor's name and notations of acronyms and trade names, class of polymer, structure, and major applications. These are followed by tabular displays showing the properties of each polymer. The maximum consistency possible has been established for properties presented with regard to format, terminology, notations, and units. However, not all properties are applicable to all polymers contained in the handbook; some properties may not even be relevant for certain polymer classes. Also, some polymers exhibit properties shown by few others (e.g., electroluminescence); these properties have been noted as "Properties of Special Interest." Each entry closes with a list of references for the reader interested in further investigation of a polymer.

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PREFACE TO THE PRINT EDITION

The *Polymer Data Handbook* offers, in a standardized and readily accessible tabular format, concise information on the syntheses, structures, properties, and applications of the most important polymeric materials. Those included are currently in industrial use or they are under study for potential new applications in industry and in academic laboratories. Considerable thought was given to the criteria for selecting the polymers included in this volume. The first criterion was current commercial importance—the use of the polymer in commercial materials—for example, as a thermoplastic, a thermoset, or an elastomer. The second criterion was novel applications—a polymer that is promising for one or more purposes but not yet of commercial importance—for example, because of its electrical conductivities, its nonlinear optical properties, or its suitability as a preceramic polymer. The hope is that some readers will become interested enough in these newer materials to contribute to their further development and characterization. Finally, the handbook includes some polymers simply because they are unusually interesting—for example, those utilized in fundamental studies of the effects of chain stiffness, self-assembly, or biochemical processes.

Based on these three criteria, more than two hundred polymers were chosen for inclusion in this work. The properties presented for each polymer include some of great current interest, such as surface and interfacial properties, pyrolyzability, electrical conductivity, nonlinear optical properties, and electroluminescence. Not all the properties are available for all the polymers included, and some properties may not even be relevant for certain polymer classes. Some polymers exhibit properties shown by few others—such as electroluminescence—and those have been presented as "Properties of Special Interest."

The handbook entries were written by authors carefully chosen for their recognized expertise in their specific polymers. The authors were asked to be highly selective, to choose and document those results that they considered to have the highest relevance and reliability. All the entries were then reviewed carefully by one or more referees, to ensure the highest quality and significance. Care was taken to achieve maximum consistency between entries, especially with regard to terminology, notations, and units. The goal was to facilitate searches in the printed version of the handbook and electronically on the online site.

Grateful acknowledgment is made here to the important contributions of the anonymous referees. It is also my real pleasure to thank a number of people at Oxford University Press for their help: specifically, Robert L. Rogers and Sean Pidgeon contributed greatly to the initiation and formulation of the basic structure of the handbook, and Matthew Giarratano carried out its implementation. It is appropriate here to thank my wife Helen for the kind of support, tangible and intangible, that makes an intimidating project, like this one, doable and sometimes even a pleasant experience.

James E. Mark
University of Cincinnati
October 1998

Nylon 3

JUNZO MASAMOTO

CLASS Aliphatic polyamides

STRUCTURE $[-CH_2CH_2CONH-]$

MAJOR APPLICATION Thermal stabilizer for polyoxymethylene, and stabilizer for polyacetal resin. Because of high amide concentration, nylon 3 shows properties of an excellent formaldehyde scavenger.⁽¹⁾

PROPERTIES OF SPECIAL INTEREST Nylon 3 shows properties of an excellent stabilizer for polyoxymethylene. Features of nylon 3 as a stabilizer for polyoxymethylene are as follows: High thermal stability, negligible decoloration when the polymer remains for a long time in injection mold machine at its molten state, and low deposit on the mold.⁽¹⁾ Nylon 3 is an interesting material as an odd-numbered nylon with shortest methylene group, thus forming high glass transition temperature and high absorption of water.

OTHER POLYMER SHOWING THIS SPECIAL PROPERTIES Formaldehyde scavenger: copolyamide composed of Nylon 6, Nylon 6,6 and Nylon 6,10.

PREPARATIVE TECHNIQUES Hydrogen transfer polymerization: Acryl amide is polymerized in the presence of a strong base catalyst (e.g., *t*-BuOK). The polymerization occurs with hydrogen transfer, producing nylon 3. The polymerization is conducted using inactive solvents, such as toluene, pyridine, chlorobenzene, and *o*-dichlorobenzene from 80 to 200°C.⁽¹⁻⁴⁾

The following methods were also reported for the preparation of nylon 3: anionic ring-opening polymerization of β -lactam (β -propiolactam);^(5,6) ring-opening polymerization of 8-ring dilactam (1,5-diazacyclooctane-2,6-dion);⁽⁷⁾ thermal polymerization of ethylene cyanehydride;⁽⁸⁾ and alternative copolymerization of carbon monoxide and ethylene imine.⁽⁹⁾

The polymerization method of α -amino acid to nylon 3 poly(β -alanine) was also studied. For example, nylon 3 was synthesized from β -alanine N-carboxyanhydride (NCA), N-dithiocarbonyl ethoxycarbonyl- β -alanine and N-carbothiophenyl- β -alanine.⁽¹⁰⁻¹²⁾

The use of various active β -alanine esters for the preparation of poly(β -alanine) was proposed.⁽¹³⁾ The direct condensation of β -alanine to obtain nylon 3 was also reported.⁽¹⁴⁾

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Molecular weight (of repeat unit)	g mol^{-1}	—	71	—
Typical molecular weight range of polymer	g mol^{-1}	Light scattering	$M_w = 90,000\text{--}120,000$	(15)
		Light scattering	$M_w = 80,000$	(2)
		Viscosity	43,000	(16, 17)
		Intrinsic viscosity in 90% formic acid	54,000	(18)

Nylon 3

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
IR (characteristic absorption frequencies)	cm ⁻¹	Amide VII for the extended planar zigzag conformation of the molecular chain	240	(19)
		Skeletal vibration of delta methylene CH ₂ CONHCH ₂)	365	(19)
		Skeletal vibration of delta methylene NCH ₂ CH ₂	465	(19)
		Amide VI	580	(19)
		Amide V	700	(19)
		NH asymmetric	3,400	(20)
		NH asymmetric	3,250	(20)
		-NH...C=O	3,070	(20)
		CH ₂ (N)	2,927	(20)
		CH ₂	2,890	(20)
		C=O amide I	1,640	(20)
		Amide II	1,530	(20)
		Amide III	1,283, 1,220	(20)
		Amide IV	1,100, 1,040, 960	(20)
		Amide V	683	(20)
Raman	cm ⁻¹	Amide VI	577	(21)
		Amide V	682	
		C-CO stretch	970	
		C-C stretch	1,110	
		NH wagging	1,227	
		Amide III	1,260	
		CH ₂ twisting	1,293	
		CH ₂ wagging	1,367	
		CH ₂ -CO bending	1,426	
		CH ₂ bending	1,443	
		Amide I	1,630	
		Symmetric CH ₂ stretching	2,853, 2,900	
		Asymmetric CH ₂ stretching	2,933	
		CH ₂ stretching	2,963/2,995	
		NH stretching	3,293	
NMR	60 MHz	¹ H NMR: trifluoroacetic acid at 60°C with Varian A 60		(3)
		¹ H NMR: D ₂ O (0.5% solution) at room temperature with a Bruker Model-WH 270 spectrometer		(22)
		¹³ C NMR: FSO ₃ H, 90.5 MHz with a Bruker WH 360 FT-NMR spectrometer		(23)
Solvents		Soluble at room temperature: formic acid, dichloroacetic acid, trifluoroacetic acid Soluble at 60°C: chloral hydrate		(24)
Nonsolvents		Insoluble at room temperature: water, methanol, butanol		(25)

Nylon 3

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Mark-Houwink parameters: K and a	$K = \text{ml g}^{-1}$ $a = \text{None}$	0.4 mol-KCl/l-HCOOH, at 35°C	$K = 1.6 \times 10^{-4}$ $a = 0.50$	(26)
Huggins constants k'	—	99 wt% formic acid: 90 wt% formic acid: 80 wt% formic acid 0.4 mol-KCl/99 wt%-HCOOH 0.4 mol-KCl/80 wt%-HCOOH	0 0.4 0.5 0.4 0.5	(27)
Lattice	—	Modification I	Monoclinic Orthorhombic	(19, 28, 29) (28)
Space group	—	—	P2 ₁ C2-2	(19) (28)
Chain conformation	—	Modification I (monoclinic), II, and III	Extended chain of planar zigzag	(19)
		Monoclinic form and orthorhombic form	Both extended	(28)
Unit cell dimensions	Å	Modification I (monoclinic)	$a = 9.33$, $b = 4.78$ (fiber identity period), $c = 8.73$	(19, 29)
(19, 29)		Monoclinic	$a = 9.60$, $b = 4.78$ (fiber identity period), $c = 8.96$	(28)
(19, 29)		Orthorhombic	$a = 9.56$, $b = 4.78$ (fiber identity period), $c = 7.56$	(19, 29)
Unit cell angles	degrees	Monoclinic, modification I	$\beta = 60$	(19)
		Monoclinic	$\beta = 122.5$	(28)
		Monoclinic	$\beta = 57.5$	(30)
Unit cell contents	monomeric units	Monoclinic form	4	(19, 28–30)
		Orthorhombic form	4	(28)
Degree of crystallinity	%	Dielectric relaxation of nylon 3 powder	38	(31)

Nylon 3

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Density	g cm ⁻³	Theoretical density for modification I	1.39	(19)
		Observed density for nylon 3 drawn fiber (modification I) at 25°C	1.33	(19)
		Observed density for nylon 3 undrawn fiber (modification II) at 25°C	1.32	(19)
		Observed density for nylon 3 for modification III at 25°C	1.33	(19)
		Theoretical density for monoclinic and orthorhombic	1.36	(28)
		Observed density for nylon 3		
		Form I (monoclinic)	1.30	(28)
		Form II (orthorhombic)	1.27	(28)
Polymorphs		Modification I (monoclinic); Modification II; Modification III; Modification IV (smectic hexagonal)		(19)
		Form I (monoclinic); Form II (orthorhombic)		(28)
Glass transition temperature	K	Tan δ maximum of drawn fiber	443–453	(32)
		DTA	384	(33)
		Dielectric relaxation of nylon 3 powder	384	(31)
		20 K min ⁻¹ , with a Perkin Elmer DSC 4	396	(34)
		NMR method, water insoluble nylon 3 in dry state	480	(18)
Melting point	K	With decomposition, water insoluble polymer	613	(2)
		With decomposition, water soluble polymer	598	(2)
		Hot stage microscope, water insoluble nylon 3	625	(18)
Sub T_g transition	K	NMR, local motion of the methylene groups of the polymer chain in amorphous region, molecular chain approach a rigid structure in this temperature range	77–130	(18)
Tensile modulus	MPa	Drawn and wet heat-treated fiber	8,000–12,000	(32)
Tensile strength	MPa	Drawn and wet heat-treated fiber	240–360	(32)
Yield strain	%	Drawn and wet heat-treated fiber	3	(32)
Maximum extensibility	%	Drawn and wet heat-treated fiber	10–20	(32)
Dielectric constant	—	10 ⁻³ –10 ⁻⁷ Hz, 30°C	4.7	(31)
Dielectric loss	—	10 ⁻³ –10 ⁻⁷ Hz, 30°C	10 ⁻² –10 ⁻¹	(31)

Nylon 3

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Decomposition temperature	K	50% weight loss, 2°C min ⁻¹ , in air	608–613	(31)
Water absorption	%	60% RH, 25°C	7	(1)
Important Patents	U.S. Patent 4,855,365 U.S. Patent 5,015,707, assigned to Asahi Chemical			
Availability	Not commercially available (only used inside Asahi Chemical Industry Company Ltd., 1-1-2, Yuraku-cho, Chiyoda-ku, Tokyo, 100 Japan)			

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Nylon 4,6

DINESH V. PATWARDHAN

TRADE NAMES Stanyl (DSM); TW300 (dry, unfilled Stanyl); TW241F10 (dry, 50% glass fiber filled Stanyl). Approximately 50 other varieties of filled or unfilled Stanyl are available.

CA NUMBER 50327-22-5⁽¹⁾

CLASS Aliphatic polyamides; Nylons

STRUCTURE $\text{H}-(\text{HN}-(\text{CH}_2)_4-\text{HN}-\text{CO}-(\text{CH}_2)_4-\text{CO})_n-\text{OH}$

PREPARATIVE TECHNIQUES Nylon 4,6 is polymerized from 1,4-diaminobutane and adipic acid; 1,4-diaminobutane is prepared separately by reacting acrylonitrile and HCN followed by hydrogenation. The first step in polymer formation involves condensing the two monomers, 1,4-diaminobutane and adipic acid, to give a low molecular weight pre-polymer. This is done at lower temperature (200°C) to avoid formation of cyclics by the amine. In a separate step, this pre-polymer is molded into uniform cylindrical pellets and heated to about 250°C in an atmosphere of nitrogen and steam. The use of pre-formed pellets is important for uniform rate of solid-state polymerization and thus the degree of polymerization. These pellets are especially important for nylon 4,6 because transamidation, which leads to uniform molecular weight, cannot be performed on the final melt due to the sensitivity of nylon 4,6 to thermal degradation. The typical molecular weight range of nylon 4,6 thus obtained is $30,000 \text{ g mol}^{-1}$ with polydispersity of 1.15.⁽¹⁻⁴⁾

MAJOR APPLICATIONS Nylon 4,6 is often blended with glass fiber or polytetrafluoroethylene and is used in underhood automotive parts, gears, electrical parts, and bearings.⁽⁵⁾

PROPERTIES OF SPECIAL INTEREST Distribution of methylene moieties in nylon 4,6 exists in regular groups of four. This high order leads to higher crystallinity and a faster rate of crystallization compared with other polyamides such as nylon 6,6 or nylon 6. Nylon 4,6 therefore has higher tensile strength, heat deflection, and tenacity, which makes it a better high-temperature engineering plastic compared with more common polyamides. On the other hand, high moisture regain is a significant drawback.^(1,3)

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Specific gravity/density	—	23°C, dry, unfilled (TW300)	1.18	(6)
Melting point	K	Dry, unfilled (TW300)	563	(6)
Specific heat	btu/lb-F	—	0.5	(5)
Solvent	—	Dry, unfilled (TW300)	95% formic acid	(4)

Nylon 4,6

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
IR (characteristic absorption frequencies)	cm ⁻¹	Obtained on thin films from formic acid solution N-H C-H ₂ Amide I-VI	3,300 (vs); 3,070 (m) 2,945 (s); 2,870 (m) 1,638 (vvs); 1,540 (vvs); 1,280 (m); 940 (w); 730 (sh); 690 (s,b); 575 (m); 520 (w)	(4)
NMR	ppm	Deuterated formic acid as the solvent ¹ H ¹³ C	1.57; 1.66; 2.37; 3.27 25.19; 25.95; 35.46; 39.65	(7)
Crystalline state properties	—	—	Monoclinic	(8)
Crystal system	—	—	<i>a</i> = 0.49, <i>b</i> = 0.53, <i>c</i> = 1.48	
Unit cell dimensions	nm	—	<i>α</i> = 51, <i>β</i> = 77, <i>γ</i> = 62	
Cell angles	Degrees	—		
Heat of fusion	kJ mol ⁻¹	Sample quenched and annealed for 5 min at 279°C	15.1	(4)
Tensile modulus	MPa	Dry, unfilled (TW300) Dry, filled (TW241F10)	3,000 16,000	(5) (9)
Tensile strength at break	MPa	Dry, unfilled (TW300)	99.31	(5)
Tensile strength at yield	MPa	Dry, unfilled (TW300) Dry, filled (TW241F10)	79.31 234.5	(5) (9)
Yield stress	MPa	Dry, unfilled (TW300)	95	(6)
Elongation at break	%	Dry, unfilled (TW300)	30	(5)
Flexural modulus	MPa	Dry, unfilled (TW300) Dry, filled (TW241F10)	3,100 14,000	(6) (9)
Flexural strength at yield	MPa	Dry, unfilled (TW300) Dry, filled (TW241F10)	149.6 350	(5) (9)
Impact strength	ft-lb/in	Izod, 73°F, dry, unfilled Dry, filled (TW241F10)	1.8 2.2	(5) (9)
Hardness	Shore D	Durameter	85	(5)

Nylon 4,6

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Poisson ration	—	—	0.37	(5)
Dielectric constant ϵ'	—	1 kHz	3.83	(5)
Resistivity	ohms cm	—	5×10^{14}	(5)
Surface resistivity	ohms	—	8×10^{15}	(5)
Thermal conductivity	btu-in/hr-ft ² -F	—	2	(5)
Water absorption	%	50% relative humidity	3	(6)
Vicat softening temperature	K	—	560.8	(5)
Distortion temperature	K	—	433	(10)
Cost	US\$ kg ⁻¹	Dry, unfilled, 1994 price	6.5	(2)
Supplier	DSM Engineering Plastics, P.O. Box 3333, 2267 West Mill Road, Evansville, Indiana 47732, USA			(9)

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Nylon 6

PAUL G. GALANTY

ACRONYM, ALTERNATIVE NAME, TRADE NAMES PA-6, poly- ϵ -caproamide, Capron[®], Ultramid[®], Nylatron[®]

CLASS Aliphatic polyamides

STRUCTURE $[-NH(CH_2)_5CO-]$

MAJOR APPLICATIONS Gears, fittings, and bearings. Electrical switches, bobbins, and connectors. Food packaging film. Monofilament for weed trimmers and fishing line. Blow and roto-molded containers. Wire and cable jacketing. Power tool housings, wheelchair wheels, automotive cooling fans, and other underhood parts.

PROPERTIES OF SPECIAL INTEREST Excellent load bearing (strength and stiffness) capability at elevated temperatures. Good chemical and abrasion resistance. Low coefficient of friction. Toughness and impact resistance.

PREPARATIVE TECHNIQUES (a) Hydrolytic polymerization of ϵ -caprolactam;⁽¹⁾ temperature = 250–260°C; pressure cycle for hydrolysis and addition; vacuum cycle for accelerated rate condensation. (b) Solid state polymerization for very high molecular weight;⁽¹⁾ temperature = 140–170°C (higher temperature causes discoloration); high vacuum to reach target molecular weight; nitrogen purge at atmospheric pressure is a costly alternative.

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Monomer	—	—	ϵ -Caprolactam	(2)
Molecular mass	g mol^{-1}	—	113.16	
Melting point	K	—	342.2	
Boiling point	K	—	543	
Bulk density	g cm^{-3}	—	0.6–0.7	
Polymerization heats of reaction	kcal mol^{-1}	Hydrolysis Addition Condensation	2.1 –4 –6.1	(3)
Repeat unit	$[-NH(CH_2)_5CO-]$			(4)
Molecular mass range	g mol^{-1}	Typical as sold Solid state	1.8–5.2 ($\times 10^4$) $\sim 1 \times 10^5$	(3)
Typical polydispersity index	—	—	1.9–2.0	(3)
IR (characteristic absorption frequencies)	cm^{-1}	Assignment N–H hydrogen-bonded stretch C=O amide I stretch C–N amide II stretch	3,300 1,640 1,545	(5)

Chemical resistance⁽⁶⁾

Chemical	Temp. (°C)	Conc. (%)	Rating			
			Excellent	Good	Poor	Severe attack
Acetone	23	100	✓			
Benzene	23	100	✓			
Ethylene glycol/water	23	50		✓		
Ethylene glycol/water	120	50				✓
Formic acid	23	90				✓
Gasoline	100	100	✓			
Gasoline/methanol (15%)	23	15			✓	
Hydrochloric acid	23	10				✓
Potassium hydroxide	23	10		✓		
Potassium hydroxide	60	20			✓	
Trichloroethylene	23	100		✓		
Water	Up to 50	100		✓		
Water (steam)	100–150	100				✓

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Lattice	—	—	Monoclinic	(7)
Unit cell dimensions	nm	α structure γ structure	$a = 0.956, b = 1.724,$ $c = 0.801$ $a = 0.933, b = 1.688,$ $c = 0.478$	(7)
Unit cell angles	Degrees	α structure γ structure	67.5 121	(7)
Unit cell contents	—	α structure γ structure	4 4	(7)
Heat of fusion	J g ⁻¹	Calorimetry	188	(8)
Density	g cm ⁻³	ASTM D-792; dry as molded	1.13	(9)
Degree of crystallinity	%	Typical molded	50	(10)
Mark-Houwink parameters: K and a	$K = \text{ml g}^{-1}$ $a = \text{None}$	In 85% formic acid; 25°C	$K = 0.023$ $a = 0.82$	(11)
Polymorphs	—	—	α, γ	(7)
Refractive index	—	At thickness < 0.5 mm; molded, undrawn	1.53	(12)
Glass transition temperature	K	DSC	320–330	(13)

Nylon 6

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Melting point	K	ASTM D-789; Fisher-Johns	493	(9)
Specific heat	J g ⁻¹ K ⁻¹	Neat, 0°C Neat, 120°C Neat, 160°C	1.38 2.30 2.68	(14)
Thermal expansion coefficient	mm (mm K) ⁻¹	ASTM D-696 Neat resin 33% glass fiber	8.30 × 10 ⁻⁴ 3.80 × 10 ⁻⁴	(9)
Deflection temperature under load	K	ASTM D-648 Neat resin Load = 1.80 MPa Load = 0.45 MPa 33% glass fiber Load = 1.80 MPa Load = 0.45 MPa	338 438 483 493	(9)
Tensile strength, yield	MPa	ASTM D-638 Neat resin DAM, 23°C* DAM, 121°C 50% RH, 23°C* 33% glass fiber DAM, 23°C DAM, 121°C 50% RH, 23°C	79 21 36 200 83 127	(9)
Tensile elongation, yield	%	ASTM D-638 Neat resin DAM, 23°C DAM, 121°C 50% RH, 23°C 33% glass fiber DAM, 23°C DAM, 121°C 50% RH, 23°C	7 15 16 3 7 6	(9)
Tensile elongation, ultimate	%	ASTM D-638 Neat resin DAM, 23°C DAM, 121°C 50% RH, 23°C 33% glass fiber DAM, 23°C DAM, 121°C 50% RH, 23°C	70 >300 260 3 7 6	(9)

Nylon 6				
PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Flexural strength	MPa	ASTM D-790		(9)
		Neat resin		
		DAM, 23°C	108	
		DAM, 121°C	17	
		50% RH, 23°C	35	
		33% glass fiber		
		DAM, 23°C	276	
Flexural modulus	MPa	ASTM D-790		(9)
		Neat resin		
		DAM, 23°C	2,829	
		DAM, 121°C	304	
		50% RH, 23°C	738	
		33% glass fiber		
		DAM, 23°C	9,384	
Notched Izod impact strength	J m ⁻¹	ASTM D-256		(9)
		Neat resin		
		DAM, 23°C	53	
		50% RH, 23°C	NB	
		33% glass fiber		
		DAM, 23°C	117	
		50% RH, 23°C	235	
Hardness, Rockwell	R scale	ASTM D-785; DAM, 23°C		(9)
		Neat resin	119	
		33% glass fiber	121	
Abrasion resistance	mg kcycles ⁻¹	ASTM D-1044, Taber; DAM, 23°C		(15)
		Neat resin	9	
		33% glass fiber	30	
Volume resistivity	ohm cm	ASTM D-257; DAM, 23°C		(9)
		Neat resin	1.00 × 10 ¹⁴	
		33% glass fiber	1.00 × 10 ¹⁵	
Surface resistivity	ohms	ASTM D-257; DAM, 23°C		(9)
		Neat resin	1.00 × 10 ¹⁵	
		33% glass fiber	1.00 × 10 ¹⁵	
Dielectric constant	—	ASTM D-150; DAM, 23°C, 1 MHz; 33% glass fiber	3.80	(9)
Dissipation factor	—	ASTM D-150; DAM, 23°C, 1 MHz; 33% glass fiber	0.022	(9)

Nylon 6

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Dielectric strength, short time	kV mm ⁻¹	ASTM D-149; DAM, 23°C, 3.2 mm		(9)
		Neat resin	460	
		33% glass fiber	560	
Thermal conductivity	W (m K) ⁻¹	—	0.23	(16)
Coefficient of friction	—	ASTM D-1894, polymer to steel		(17)
		Neat resin		
		Static	0.24	
		Dynamic	0.16	
		33% glass fiber		
		Static	0.25	
		Dynamic	0.16	
Thermal index ratings	K	UL-746B; 60,000-h half-life at indicated temperature; 3.2 mm		(9)
		Neat resin		
		Mechanical	378	
		Impact	378	
		Electrical	403	
		33% glass fiber		
		Mechanical	413	
		Impact	393	
		Electrical	413	
Moisture absorption	%	ASTM D-570; 23°C		(9)
		Neat resin		
		50% RH equilibrium	2.7	
		Saturation	9.5	
		33% glass fiber		
		50% RH equilibrium	1.9	
		Saturation	6.7	
Flammability ratings		UL-94; 3.2 mm		(9)
		Neat resin	V-2	
		33% glass fiber	HB	
Price	US\$ kg ⁻¹	Commercial quantities of 2-5 (×10 ⁵) kg yr ⁻¹		(18)
		Neat resin	0.66–0.68	
		33% glass fiber	0.68–0.70	
Major suppliers	AlliedSignal, Morristown, New Jersey BASF, Mt. Olive, New Jersey Bayer, Pittsburgh, Pennsylvania Custom Resins, Henderson, Kentucky DuPont, Wilmington, Delaware Nylatech, Manchester, New Hampshire			

*DAM = tested dry as molded; 50% RH = tested after equilibration in a 50% RH, 23°C room.

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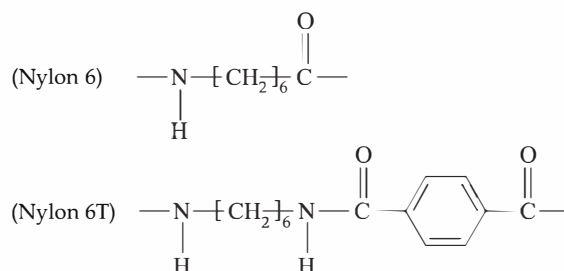
Nylon 6 copolymer

SHAW LING HSU

TRADE NAME, ALTERNATIVE NAMES Ultramid T (BASF), nylon 6/6T, polyphthalamide

CLASS Aromatic polyamides; aromatic nylon

STRUCTURE These aromatic nylons consist of aliphatic and aromatic building blocks incorporating the repeat units of nylon 6—poly(caprolactam)—and nylon 6T—poly(hexamethylene terephthalamide). Because of this composition, Ultramid T resins are often designated as nylon 6/6T materials. The basic structure is nylon 6/6T, with a majority component of nylon 6.



PROPERTIES OF SPECIAL INTEREST Extremely high melting temperature can be achieved by adjusting the relative amount of the aromatic component. Good mechanical properties at elevated temperatures. Good resistance to chemicals. Good dielectric properties. Dimensional stability in the presence of moisture. Low moisture absorption, good impact resistance, good dielectric properties, good resistance to chemicals, easy to process.

MAJOR APPLICATIONS High-temperature applications, automobile parts (e.g., radiator, ventilation, and fuel supply systems), electronics housings, plug and socket connectors, printed circuit boards, tennis rackets, golf clubs.

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
NMR*	ppm	Range for amide proton peaks Range for methylene proton peaks	6–7 1–4	(1)
IR (characteristic absorption frequencies)	cm ⁻¹	Overall, the infrared spectrum greatly resembles those found for other polyamides. The principal spectroscopic features can be definitively assigned. N–H stretching Amide I Amide II Range for symmetric and asymmetric methylene stretching vibrations Methylene bending vibrations	3,305 1,627 1,545 3,000 1,400	(2, 10) (2, 10) (2, 10) (3–7, 9–15) —

Nylon 6 copolymer				
PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
IR (characteristic absorption frequencies)	cm ⁻¹	Other specific spectroscopic features can be linked to the presence of the nylon 6T component		(16, 17)
		Vibrations assignable to para-disubstituted aromatic units	862, 1,019, ~1,300, [†] 1,498	(3, 8, 18)
Melting tempuratu [‡]	K	—	583–613	(20, 21)
Glass transition temperature	K	—	473	(21)
Degradation of aromatic polyamides		Plasma treatment can modify aromatic nylons reducing the concentration of amide units relative to that in untreated nylon 6,6 copolymer. When these polyamides are dissolved in acidic solution, the polyamid is gradually degraded.		(22)
Density	g cm ⁻³	—	1.18	(20)
Linear thermal expansion coefficient	%	60°C	0.2	(20)
Tensile modulus	MPa	Dry and moist	3,200	(20)
Tensile strength	MPa	Dry Moist	100 90	(20)
Heat deflection temperature	K	At 624 psi	473	(20)
Dielectric constant	—	1 MHz	4.0	(20)
Moisture absorption	%	23°C, saturation	7	(21)
		23°C, 50% RH	1.8	(20)
Solvents		Hexafluoroisopropanol (HFIP)		(22)

*Both assignments fall into the range of peak positions listed for these groups in standard NMR tables.

[†]Broad features.

[‡]A broad melting behavior starts at approximately 483 K and ends at approximately 563 K. These trends are consistent with the melting behaviors reported for nylon 6/6T copolymers.⁽¹⁹⁾

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Nylon 6 copolymer

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Nylon 6,6

BRENT D. VIERS

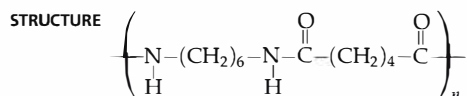
COMMON NAME Poly(hexamethylene adipamide)

IUPAC NOMENCLATURE Poly[imino(1,6-dioxohexamethylene) imnohexamethylene], poly[iminoadipolyiminohexamethylene]

TRADE NAMES Zytel (DuPont), Maranyl (ICI), Ultramid A (BASF)

CAS REGISTRY NUMBERS 32131-17-2

CLASS Aliphatic polyamides



MAJOR APPLICATIONS Gear teeth, pinions, ball bearing cages, switch parts, spools, electro-insulating parts; semfinished products, pipes, profiles; machine parts, parts subject to wear such as friction bearings, roller bearing cages, engine parts, water pump impellers, and also parts of door locks; fan and blower wheels, parts of housings, fuel filters, clips, chain tension rails; sliding bearings for swivel chairs and folding tables, sliding feet and fittings, connecting parts in furniture making; patio and party furniture.

PROPERTIES OF SPECIAL INTEREST High mechanical strength, great rigidity, good deep-drawing behavior, good dimensional stability under heat, good toughness even at low temperatures, favorable tribological properties, good resistance to chemicals, very good electro-insulating properties, good dimensional stability, rapid processing. Relatively high T_m and T_g for aliphatic polyamides (used in synthetic fibers; can be toughened as resin).

OTHER POLYMERS SHOWING THIS SPECIAL PROPERTY Poly(ϵ -caprolactam) (Nylon 6). (See also the entry on *Nylon 6* in this handbook.)

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Type of polymerization	—	Interfacial, melt	Condensation between hexamethylene diamine and adipic acid	—
Enthalpy of reaction $-\Delta H_a$	kJ mol^{-1}	Decrease in temperature shifts equilibrium to higher molecular weight	25–29 (average) 42–46 (limit)	(1)
Side products	1–2% of cyclic oligomers (14 membered ring)			(1)

Nylon 6,6

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Kinetic parameters	—	Second order kinetics, not accelerated by catalysts	Conversion <90%	(2, 3)
		Third order kinetics, carboxyl catalyzed, low water	Conversion >90%	(1, 4)
Typical comonomers	—	Aliphatic amines	Heptamethylene diamine, octamethylene diamine, decamethylene diamine, cyclohexyl diamine	—
		Aliphatic diacids (sometimes diacid chlorides)	Sebacic acid, undecanedioic acid, suberic acid	
		Aromatic amines Aromatic diacids/diacid chlorides	<i>p</i> -Xylenediamine Terephthalic acid, phenylenedipropionic acid	
Molecular weight (of repeat unit)	g mol ⁻¹	—	226.3	—
Degree of branching	Can be controlled by controlled copolymerization of polyfunctional amines/acids			—
Typical molecular weight range of polymer	g mol ⁻¹	High conversion (<i>p</i> > 0.99) (lowered by monofunctional end-blockers)	12,000–20,000	(1)
Typical polydispersity index (<i>M_w/M_n</i>)	—	Most probable	2 (expected)	(1)
		Undergoes amide interchange reactions (broadened by incorporation of multifunctional units)	1.7–2.1 (by GPC)	
Typical viscosity averages	—	Relative viscosity: 8.4% solution in 90% formic acid	$\eta_r = 30\text{--}70$	—
		Inherent viscosity: 0.5 g/100 cm ³ in <i>m</i> -cresol	$\eta_{\text{inh}} = 1 \text{ dl g}^{-1}$	
IR (characteristic absorption frequencies)	cm ⁻¹	NH wag (broad)	700	(5, 6)
		CH ₂ rock	722	
		N–C=O skeletal vibration	1,170	
		N–C=O skeletal vibration	1,200	
		CH ₂ wag	1,370	
		CH ₂ symmetric scissors deformation (CH ₂ next to C=O)	1,420	
		CH ₂ symmetric scissors deformation (CH ₂ next to N)	1,440	

Nylon 6,6

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
IR (characteristic absorption frequencies)	cm^{-1}	CH ₂ symmetric scissors deformation	1,460	(5, 6)
		NH bend/C-N stretch	1,540	
		Amide C=O stretch	1,640	
		CH ₂ symmetric stretch	2,860	
		CH ₂ asymmetric stretch	2,920	
		2× NH bend (1,540) overtone	3,100	
		NH stretch	3,300	
NMR	s^{-1}	¹³ C NMR T ₁ relaxation times		(7)
		Amorphous	1.37	
		Meso	9.2	
		Crystalline	82.5	
Thermal expansion coefficients	$\text{K}^{-1} (\times 10^{-4})$	Zytel ASTM D 696	0.81	(8)
		Crystalline, volumetric 20°C	2.8	(9)
		Linear crystalline, 20°C	7–10	(10)
		Linear crystalline, 100°C	10–14	(10)
		Triclinic, α_a	2.1	(11)
		Triclinic, α_c	22.0	(11)
Compressibility coefficients	$(\text{MPa})^{-1}$ ($\times 10^{-6}$)	Pressure/temperature dependence		
		50 MPa, 20°C	62	(12)
		100 MPa, 20°C	58	(12)
		150 MPa, 20°C	54	(12)
		300 MPa, 20°C	50	(12)
		50 MPa, 120°C	125	(12)
		100 MPa, 120°C	115	(12)
		150 MPa, 120°C	95	(12)
		300 MPa, 120°C	75	(12)
Molar volume	$\text{cm}^3 \text{mol}^{-1}$	>100 MPa, 200°C	>300	(13)
		20°C, nylon rods	193	(9)
		20°C, amorphous	207.5	(14)
		20°C, amorphous group contribution calculation	208.3	(14)
Density (amorphous)	g cm^{-3}	Zytel ASTM D 792, 23°C	1.14	—
Solvents		Room temperature: trifluoroethanol, trichloroethanol, phenols, chloral hydrate, formic acid, chloro-acetic acid, HF, HCl, methanol, H ₂ SO ₄ , phosphoric acid, benzyl alcohol, ethylene chlorohydrin, 1,3 chloropropanol, 2-butene-1,4,diol., diethylene glycol, acetic acid, formamide, DMSO		—
Nonsolvents		Hydrocarbons, aliphatic alcohols, chloroform, diethyl ether, aliphatic ketones, esters		—

Nylon 6,6

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Chemical resistances		Acid resistance: limited; attacked by strong acids; general order of resistance nylon 6,12 > nylon 6,6 > copolymers or nylon 6 Base resistance: Excellent at room temperature; attacked by strong bases at elevated temperatures Solvent resistance: generally excellent; some absorption of such polar solvents as water, alcohols, and certain halogenated hydrocarbons causing plasticization and dimension changes		(8)
Solubility parameter	(MPa) ^{1/2}	δ	27.8	(15)
			24.02	(16)
			22.87	(17)
		Dispersive component δ_D	18.62	(16, 17)
		Polar component δ_P	5.11	(16)
		Hydrogen bonding component δ_H	14.12	(17)
			12.28	(16)
Theta temperature Θ	K	Carbon tetrachloride/ <i>m</i> -cresol/ cyclohexane	293	(18)
		Formic acid/ KCl/H ₂ O	298	(19, 20)
Second virial coefficient A_2	mol cm ³ g ⁻² ($\times 10^{-4}$)	<i>m</i> -Cresol, 60°C, $M_n = 18,000$	183	(21)
		Formic acid (90%), 25°C, $M_n = 18,000$	840	(22)
		Formic acid (90%)/0.2–2.5 M KCl, 25°C, $M_n = 31,000$		(20)
		At 0.2 M KCl	59.2	
		At 2.5 M KCl	7.0	
		Formic acid (90%)/2.3 M KCl, 25°C, $M_n = 31,000$	0	(20)
		Formic acid (82.5–40%), 2 M KCl, 25°C, $M_n = 31,000$		(20)
		At 82.5%	−9.4	
		At 40%	36.5	
		Formic acid (90%), 2 M KCl, 2,000 < M_n < 52,000		(18)
		At 2,000 M_n	312	
		At 52,000 M_n	10.1	
		Formic acid (75–98%), 0.5 M NaHCOO, 2,2,3,3-tetrafluoropropanol, 25°C, $M_n = 32,000$	1.0–4.0	(23)
		2,2,3,3-tetrafluoropropanol, 0.1 M sodium trifluoroacetate, 25°C, $M_n = 62,000$	57.1	(24)

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Fractionation	—	Fractional precipitation	<i>m</i> -Cresol/cyclohexane	(25, 26)
			Phenol/H ₂ O	(27)
		Turbidimetric titration	<i>m</i> -Cresol/cyclohexane	(28)
			<i>m</i> -Cresol/ <i>n</i> -heptane	(29)
		Chromatography	Methylene chloride	(30)
		Gel permeation	Hexafluoroisopropanol	(31)
		Partition chromatography, 20°C	Formic acid/H ₂ O (88%)	(32)
		Sedimentation gradient: ultracentrifugation	Carbon tetrachloride/ <i>m</i> -cresol/cyclohexane	(19)
		Continuous immiscible liquid distribution	Phenol/water	(33)
Mark-Houwink parameters: <i>K</i> and <i>a</i>	<i>K</i> = ml g ⁻¹ <i>a</i> = None	<i>o</i> -Chlorophenol, 25°C, 14,000 < <i>M_n</i> < 50,000	<i>K</i> = 168, <i>a</i> = 0.62	(34)
		<i>m</i> -Cresol, 25°C, 14,000 < <i>M_n</i> < 50,000	<i>K</i> = 240, <i>a</i> = 0.61	(34)
		<i>m</i> -Cresol, 25°C, 150 < <i>M_n</i> < 50,000	$[\eta] = 0.5 + 0.0353M^{0.792}$	(18)
		Dichloroacetic acid, 25°C, 150 < <i>M_n</i> < 50,000	$[\eta] = 0.5 + 0.0352M^{0.551}$	(18)
		2,2,3,3-Tetrafluoropropanol/ CF ₃ COONa (0.1 M), 25°C, 14,000 < <i>M_n</i> < 50,000	<i>K</i> = 114, <i>a</i> = 0.66	(34)
		Aqueous HCOOH (90 vol%), 25°C 6,000 < <i>M_n</i> < 65,000	<i>K</i> = 35.3, <i>a</i> = 0.786	(34)
		5,000 < <i>M_n</i> < 25,000	<i>K</i> = 110, <i>a</i> = 0.72	(27)
		14,000 < <i>M_n</i> < 50,000	$[\eta] = 2.5 + 0.0132M^{0.873}$	(18)
		HCOOH (90%)/HCOONa (0.1 M), 25°C 10,000 < <i>M_n</i> < 50,000	<i>K</i> = 32.8, <i>a</i> = 0.74	(34)
		14,000 < <i>M_n</i> < 50,000	<i>K</i> = 87.7, <i>a</i> = 0.65	(34)
		150 < <i>M_n</i> < 50,000	$[\eta] = 1.0 + 0.0516M^{0.687}$	(18)
		HCOOH (90%)/KCl (2.3 M), 25°C 14,000 < <i>M_n</i> < 50,000	<i>K</i> = 227, <i>a</i> = 0.50 (<i>θ</i>)	(34)
		150 < <i>M_n</i> < 50,000	<i>K</i> = 253, <i>a</i> = 0.50 (<i>θ</i>)	(18)
		H ₂ SO ₄ (95%), 25°C, 150 < <i>M_n</i> < 50,000	$[\eta] = 2.5 + 0.0249M^{0.832}$	(18)
		H ₂ SO ₄ (96%), 25°C, 14,000 < <i>M_n</i> < 50,000	<i>K</i> = 115, <i>a</i> = 0.67	(34)
		Melt polymer, high molecular weight	<i>a</i> = 3.5	(35, 36)
		Formic acid, 25°C		(37)
		$[\eta] = 83 \text{ ml g}^{-1}$	0.20	
		$[\eta] = 100 \text{ ml g}^{-1}$	0.22 ± 0.01	
		$[\eta] = 120 \text{ ml g}^{-1}$	0.24 ± 0.02	
		$[\eta] = 140 \text{ ml g}^{-1}$	0.27 ± 0.02	
		$[\eta] = 160 \text{ ml g}^{-1}$	0.27 ± 0.02	
		$[\eta] = 180 \text{ ml g}^{-1}$	0.28 ± 0.02	
		$[\eta] = 200 \text{ ml g}^{-1}$	0.29 ± 0.01	
Huggins constants: <i>k_H</i>	—			

Nylon 6,6

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Schulz-Bakke coefficients k_{SB}	—	Formic acid, 25°C $[\eta] = 83 \text{ ml g}^{-1}$ $[\eta] = 100 \text{ ml g}^{-1}$ $[\eta] = 120 \text{ ml g}^{-1}$ $[\eta] = 140 \text{ ml g}^{-1}$ $[\eta] = 200 \text{ ml g}^{-1}$	0.20 0.22 ± 0.02 0.24 ± 0.02 0.26 ± 0.02 0.28 ± 0.01	(37)
Characteristic ratio $\langle r^2 \rangle_0 / nl^2$	—	HCOOH (90%), 25°C HCOOH (90%)/KCl 2.3 M, 25°C	5.3 6.85 5.95	(25, 27) (22) (38, 39)
End-to-end distance $r_0 / M^{1/2}$	nm ($\times 10^{-4}$)	HCOOH (90%), 25°C HCOOH (90%)/KCl 2.3 M, 25°C	890 ± 40 1,010 935	(25, 27) (22) (38, 39)
Lattice (monoclinic, etc.)	—	—	(α) I: triclinic (α) I: monoclinic (α) II: triclinic (β) triclinic (high temperature) triclinic (170°C)	—
Space group	—	—	CI-1	—
Chain conformation (ρ_n of helix)	—	—	$14^*1/1$	—
Unit cell dimensions	Å		<i>a</i> <i>b</i> <i>c</i>	
		α I: monoclinic	15.7 10.5 17.3	(40)
		α I: triclinic	4.9 5.4 17.2	(41)
			5.00 4.17 17.3	(42)
			4.87 5.26 17.15	(43)
			4.97 5.47 17.29	(44)
		α II: triclinic	4.95 5.45 17.12	(44)
		β triclinic	4.9 8.0 17.2	(45)
		High temperature (170°C)	5 5.9 16.23	(46)
Unit cell angles	Degrees		α β γ	
		α I: monoclinic	— 73 —	(40)
		α I: triclinic	48 77 63	(41)
			81 76 63	(42)
			50 76 64	(43)
			48 77 62	(44)
		α II: triclinic	52 80 63	(44)
		β triclinic	90 77 67	(45)
		High temperature	57 80 60	(46)

Nylon 6,6

PROPERTY	UNITS	CONDITIONS		VALUE	REFERENCE	
Unit cell contents (number of repeat units)	—	α I: monoclinic		9	(40)	
		α I: triclinic		1	(42–44)	
		α II: triclinic		1	(44)	
		β triclinic		2	(45)	
		High temperature		1	(46)	
Bragg spacings	—	<i>hkl</i>	<i>d</i> -value (nm)	2θ (degrees)	Relative intensity	(45)
		002	0.641	13.83	w	
		100, 010, 110	0.390	22.96	vvs	
		015	0.335	26.65	w	
		110, 210	0.236	38.12	s	
		017, 127	0.233	38.69	w	
		117, 027	0.218	41.37	w	
		117, 227	0.194	46.71	w	
		020, 220	0.183	49.70	s	
Degree of crystallinity	As shown	General range	40–60%		(1)	
		General equation based on density	$\alpha = 830\text{--}(900/\rho)\%$		(10)	
		IR determination	Crystalline = 852 cm^{-1} Amorphous = $1,140\text{ cm}^{-1}$		(1)	
Heat of fusion	kJ mol^{-1}	α I triclinic	46.5		(47)	
			40		(47)	
			36.8		(48)	
			68		(48)	
			58		(48)	
			46.9		(49)	
		α II triclinic	53.2		(44)	
			43.4		(44)	
			41.9		(50)	
Heat of fusion (per repeat unit)	J g^{-1}	α II triclinic	191.9		(44)	
Entropy of fusion	$\text{J K}^{-1}\text{ mol}^{-1}$	—	83–86		(10)	
			79.9		(44)	
Density (crystalline)	g cm^{-3}	α I triclinic	1.220		(40)	
			1.24		(41)	
			1.241		(42)	
			1.225		(43)	
			1.204		(44)	
		α II triclinic	1.152		(44)	
			1.165		(45)	
			1.25		(46)	
		β , triclinic	1.10		(5)	
		High temperature (170°C) triclinic				
		Crystalline molded	1.09		(51)	
			1.13–1.145		(51)	

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE		
Density (amorphous)	g cm ⁻³	<i>a</i> I triclinic	1.09	(52)		
			1.12	(53)		
			1.069	(54)		
			1.095	(50)		
		<i>a</i> II triclinic <i>b</i> , triclinic Amorphous molded Melt, 270°C	1.095	(44)		
			1.09	(53)		
			0.989	(51)		
			1.248	(5)		
Crystal modulus	dynes cm ⁻²	α 1	175 × 10 ⁴	(7)		
Polymorphs (listing)	—	—	α I, α II, β, high temperature	—		
Crystal growth activation energy	kJ mol ⁻¹	—	64.5	(10)		
Maximum crystallization rate	—	150°C	—	(7)		
Growth rate (<i>T</i> _f = fusion temperature; <i>T</i> _c = crystallization temperature)	μm s ⁻¹ nm s ⁻¹	Maximum linear growth			20	(51)
		<i>M</i> _n × 10 ³	<i>T</i> _f (°C)	<i>T</i> _c (°C)		
		11.6	295	241	166.7	(55)
				247	58.35	(55)
			295	250	13.84	(55)
				295	252	10.50
			285	247	66.08	(55)
				262 (10 min)	251	14.21 (negative spherulites)
			256	83.4	(56)	
				257	13.3	(57)
				259	9.17	(57)
				261	6.67	(57)
				263	4.17	(57)
				265	2.50	(57)
		12.9	300 (30 min)	246	106.7	(58)
				248	56.34	(58)
				253	10.84	(58)
		13.7	300 (30 s)	141	13,502.7	(59)
				160	13,669.4	(59)
				180	12,119.1	(59)
				199	8,901.8	(59)
				215	5,167.7	(59)
				230	2,117.1	(59)
				234	1,530.3	(59)
				237	920.18	(59)
				239.5	765.15	(59)
				241	471.76	(59)
				244	368.40	(59)

PROPERTY	UNITS	CONDITIONS			VALUE	REFERENCE
Growth rate (T_f = fusion temperature; T_c = crystallization temperature)	nm s^{-1}	$M_n \times 10^3$	T_f ($^{\circ}\text{C}$)	T_c ($^{\circ}\text{C}$)		
		14.6	280	241.5	283.39	(58)
				243	230.05	(58)
				245	180.86	(58)
				248	33.685	(58)
				252	14.66	(58)
			300	241.5	204.4	(58)
				243	175.0	(58)
				245	128.3	(58)
				248	58.34	(58)
		14.6	300	252	$G = 5.501$	(60)
			315	241.5	280.0	(60)
				243	168.4	(60)
				245	113.4	(60)
				248	56.68	(60)
				252	6.335	(60)
		25.5 (M_w)		50	3,650.7 (positive spherulites)	(60)
				100	4,706.6	(60)
				142	6,751.3	(60)
				160	6,101.2	(60)
				178	5,201.0	(60)
				198	3,700.7	(60)
				200	12,900.6	(60)
				228	466.7	(60)
		25.5	300	180	11,435.6 (positive spherulites)	(60)
				200	7,951.5	(60)
				211	5,284	(60)
				220	2,733.8	(60)
				230	1,615.3	(60)
				235.5	680.13	(60)
				240	483.4	(60)
Hoffman-Lauritzen theory constants						(55)
Growth rate constant G_0	cm s^{-1}	—			1.55×10^3	
Diffusion activation energy U^*	cal mol^{-1}	—			167	
Chain dimensions	$\text{\AA}$	—			$a_0 = 4.76, b_0 = 3.70$	
Nucleation rate constant K_g	K^2	—			1.02×10^5	
Lateral surface free energy σ	erg cm^{-2}	—			8.0	
Fold surface free energy σ_e	erg cm^{-2}	—			40	
Melting point (equilibrium)	K	T_m (determined by $T_m - T_c$ extrapolation)			542.2	(44)

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Deformation induced crystallization	—	Spinning effects	—	(7)
Glass transition temperature	K	Dependent on relative humidity (water plasticized)	320–330	(1)
		Oven dry	351	(7)
		50% RH	308	(7)
		100% RH	258	(7)
Melting point	K	General	537	—
		α I: monoclinic	543	
		α I: triclinic	534–574	
		α II: triclinic	542.5	
Sub- T_g transition temperatures	K	β (plasticized glass transition)		
		At 11 Hz	363	(61)
		—	357	(62)
		At 1 Hz	370	(63)
		γ (amide hydrogen bond motions with sorbed H_2O)		
		At 40–600 Hz	249	(64)
		—	245	(62)
		δ (methylene group motion)		
		At 40–600 Hz	156	(64)
		—	186	(62)
Heat capacity (of repeat units)	$\text{kJ kg}^{-1} \text{K}^{-1}$	DSC annealed nylon solid	1.4	(65)
Deflection temperature	K	Zytel ASTM D 648		(8)
		0.5 MPa	508	
		1.8 MPa	363	
Tensile modulus	MPa	Nylon 23°C	3,300	(10)
		Nylon 23°C moist ISO-1110	1,700	
		Nylon, 100°C	600	
Bulk modulus	MPa	Nylon dry crystalline rods	3,300	(10)
Shear modulus	MPa	23°C	1,300	(10)
		23°C (nucleated)	1,700	
		100°C	300	
		200°C	150	
Shear strength	MPa	Zytel Resins ASTM D 732, 23°C	66.8–72.4	(8)
		50% relative humidity, 23°C	63.4–68.9	
Storage modulus	MPa	0.1–110 Hz	5–100	(7)

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Loss modulus	—	0.1–110 Hz, $\log \tan \delta$	–1.3 to 0.9	(7)
Tensile strength	MPa	Zytel Resins ASTM D 638		(8)
		–40°C	113.8–128.9	
		23°C	82.7–90.3	
		77°C	58.6–62.1	
		121°C	42.7–47.6	
		50% relative humidity		
		–40°C	110.3–117.2	
		23°C	62.1–77.2	
		77°C	40.7–50.3	
		121°C	32.4–42.1	
Yield stress	MPa	Zytel Resins ASTM D 638		(8)
		–40°C	113.8–128.9	
		23°C	82.7–90.3	
		77°C	44.8–58.6	
		121°C	33.1–34.5	
		50% relative humidity		
		–40°C	110.3–117.2	
		23°C	58.6–62.1	
		77°C	39.3–40.7	
		121°C	27.6–32.4	
Yield strain $(L/L_0)_y$	%	Zytel Resins ASTM D 638		(8)
		–40°C	4–5	
		23°C	4–5	
		77°C	25–30	
		121°C	30–45	
		50% relative humidity		
		–40°C	5	
		23°C	25–30	
		77°C	30	
		121°C	30–40	
Maximum extensibility $(L/L_0)_r$	%	Zytel ASTM D 638		(8)
		–40°C	10–15	
		23°C	30–60	
		77°C	145–>300	
		121°C	200–>300	
		50% relative humidity		
		–40°C	15–35	
		23°C	200–>300	
		77°C	250–>300	
		121°C	>300	

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Flexural modulus	MPa	Zytel ASTM D 790 -40°C 23°C 77°C 121°C 50% relative humidity -40°C 23°C 77°C 121°C	3,241-3,516 2,827-2,964 689-724 538-552 3,447 1,207-1,310 565-586 414	(8)
Impact strength	J m ⁻¹	Zytel ASTM D 256 Izod -40°C 23°C 50% relative humidity Izod -40°C 23°C	32 53-64 27 112-133	(8)
	kJ m ⁻²	Zytel ASTM D 1822 tensile impact, 23°C Long specimen 50% RH long specimen Short specimen 50% RH short specimen	 504 1,470 157 231	
Compressive strength	MPa	20°C nylon molded 2.5% H ₂ O 1% strain 2% strain 4% strain 6% strain	14 28 56 70	(10)
Hardness	—	Zytel ASTM D676 Durometer 50% Relative humidity	89 82	(8)
Poisson ratio	—	General extruded rod 100°C Melt	0.41 0.38 0.44 0.5	(8) (10) (10) (10)
Abrasion resistance	g MHz ⁻¹	Zytel Taber abrasion CS-17 wheel, 1,000 g	4-7	(8)
Refractive index increment <i>dn/dc</i>	ml g ⁻¹	(All data at 25°C) Formic acid 90% + 0.5 M sodium formate Trifluoroethanol Acetone	(Source wavelength noted) 0.137 (436 nm) 0.228 (436 nm) 0.076 (436 nm)	(66) (66) (67)
(Trifluoroacetylated nylon 6,6)				

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Refractive index increment dn/dc	ml g ⁻¹	(All data at 25°C)	(Source wavelength noted)	
		Formic acid		
		75%	0.144 (633nm)	(39)
		80%	0.145 (633nm)	(39)
		85%	0.141 (436 nm)	(68)
		90%	0.145 (633nm)	(20, 39)
		90%	0.145 (546nm)	(18)
		90%	0.145 (436 nm)	(68)
		95%	0.150 (633nm)	(39)
		100%	0.157 (633nm)	(39)
		100%	0.1525 (436nm)	(69)
		Formic acid + KCl		(20)
		85% + 2.0 M KCl	0.124 (633nm)	
		90% + 0.2 M KCl	0.143 (633nm)	
		90% + 0.5 M KCl	0.140 (633nm)	
		90% + 1.0 M KCl	0.136 (633nm)	
		90% + 1.5 M KCl	0.131 (633nm)	
		90% + 2.0 M KCl	0.126 (633nm)	
		90% + 2.5 M KCl	0.122 (633nm)	
		95% + 2.0 M KCl	0.129 (633nm)	
		Formic acid + sodium formate		(39)
		75% + 0.5 M NaHCOO	0.138 (633nm)	
		80% + 0.5 M NaHCOO	0.136 (633nm)	
		90% + 0.02 M NaHCOO	0.147 (633nm)	
		90% + 0.05 M NaHCOO	0.146 (633nm)	
		90% + 0.10 M NaHCOO	0.142 (633nm)	
		90% + 0.2 M NaHCOO	0.142 (633nm)	
		90% + 0.5 M NaHCOO	0.136 (633nm)	
		90% + 0.75 M NaHCOO	0.130 (633nm)	
		90% + 1.0 M NaHCOO	0.124 (633nm)	
		95% + 0.5 M NaHCOO	0.136 (633nm)	
		100% + 0.5 M NaHCOO	0.136 (633nm)	
		Tetrafluoropropanol	0.190 (546 nm)	(24)
		Tetrafluoropropanol + 0.1 N sodium trifluoroacetate buffer	0.190 (436 nm)	(24)
Birefringence	—	$n_{ }$	1.582	(51)
		$n_{\perp}$	1.519	(9)
Dielectric constant ϵ'	—	Zytel ASTM D 150		(8)
		1 × 10 ² Hz	4.0	
		1 × 10 ³ Hz	3.9	
		1 × 10 ⁶ Hz	3.6	
		1 × 10 ² Hz	8.0	
		50% relative humidity		
		1 × 10 ³ Hz	7.0	
		1 × 10 ⁶ Hz	4.6	
		—	(See also table below)	

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Dielectric constant ϵ'

Temp. (°C)	10 ² Hz	10 ³ Hz	10 ⁴ Hz	10 ⁵ Hz	10 ⁶ Hz	10 ⁷ Hz	10 ⁸ Hz	10 ⁹ Hz
−30	120	105	105	130	165	160	100	49
0	110	120	135	160	200	200	160	81
30	85	125	180	215	250	255	220	135
60	810	590	460	390	370	360	320	240
90	2,000	1,450	1,300	1,450	1,600	1,300	810	440
20 (50% RH)	1,100	1,020	1,000	900	700	450	280	170

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Dielectric tan δ	—	Nylon (coupled with above table) values given as $\tan \delta \times 10^4$	See table below	(10)

Dielectric tan δ

Temp. (°C)	10 ² Hz	10 ³ Hz	10 ⁴ Hz	10 ⁵ Hz	10 ⁶ Hz	10 ⁷ Hz	10 ⁸ Hz	10 ⁹ Hz
−30	3.1	3.1	3.1	3.0	3.0	3.0	3.0	3.0
0	3.3	3.3	3.2	3.2	3.1	3.0	3.0	3.0
30	3.6	3.5	3.4	3.4	3.2	3.1	3.1	3.0
60	5.0	4.6	4.3	4.0	3.7	3.5	3.3	3.1
90	10	8.9	7.6	6.2	5.0	4.0	3.4	3.2
20 (50% RH)	7.5	5.9	4.8	4.1	3.7	3.4	3.3	3.2

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Dielectric strength	V cm ^{−1}	VDE 0303, part 2, IEC-243, electrode K20/P50 Dry Dry, 100°C Moist ISO-1110	120×10^{-4} 40×10^{-4} 80×10^{-4}	(10)
Dissipation factor	—	Zytel ASTM D 150 1×10^2 Hz 1×10^3 Hz 1×10^6 Hz 50% relative humidity 1×10^2 Hz 1×10^3 Hz 1×10^6 Hz	0.01 0.02 0.02 0.2 0.2 0.1	(8)
Resistivity	ohm cm	Zytel ASTM D 257 Zytel ASTM D 257, 50% RH Nylon, 20°C, 50% RH Nylon, 20°C, 100% RH Nylon, 60°C Nylon, 100°C Nylon, 100°C, 50% RH	1×10^{15} 1×10^{13} 3×10^{11} 1×10^9 6×10^{11} 3×10^9 4×10^7	(8) (8) (10) (10) (10) (10) (10)

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Thermally stimulated current	—	Relaxation, humidity effects	—	(7)
Surface tension	mN m ⁻¹	Nylon, $M_n = 17,000$, $M_w = 35,000$		
		20°C	46.5	(70)
		150°C	38.1	
		200°C	34.8	
		280°C	29.6	
		325°C	26.7	
		$-d\gamma/dT$	0.065	(41, 70)
		γ_{LV} at 20°C	46.4	(41)
		Zisman critical wetting surface tension, γ_c	42.5	(71)
Contact angle θ	Degrees	Water	72	(72)
Surface free energy	mJ m ⁻²	Dispersive, γ^D	40.8	(72)
		Polar, γ^P	6.2	(72)
		Lifschitz-van Der Waals, γ^{LW}	36.4	(73)
		Lewis Acid Base, γ^{AB}	1.3	(73)
		Electron acceptor parameter, γ^+	0.02	(73)
		Electron donor parameter, γ^-	21.6	(73)
Interfacial tension	mN m ⁻¹ mN m ⁻¹ K ⁻¹	Polyethylene, γ_{12} at 20°C	14.9	(70)
		$-d\gamma/dT$	0.018	
Adhesive bond strength	MPa	Nylon-aluminum tensile	68	(74)
		Nylon-steel tensile	70	
		Nylon-copper tensile	76	
Diffusion coefficient	cm ² s ⁻¹	H ₂ O, 20°C	0.02×10^{-8}	(10)
		H ₂ O, 60°C	3.5×10^{-8}	(10)
		H ₂ O, 100°C	25×10^{-8}	(10)
		CO ₂ , 5°C, undrawn fiber	1.8×10^{-10}	(75)
		CO ₂ , 25°C, undrawn fiber	8.3×10^{-10}	(75)
		CO ₂ , 5°C, drawn fiber	1.8×10^{-10}	(75)
		CO ₂ , 25°C, drawn fiber	4.8×10^{-10}	(75)
Activation energy for diffusion	kJ mol ⁻¹	H ₂ O	58	(10)
Permeability coefficient	cm ³ (STP) cm s ⁻¹ cm ⁻² Pa ⁻¹	CO ₂ , 5°C, undrawn fiber	0.018×10^{-13}	(75)
		CO ₂ , 25°C, undrawn fiber	0.052×10^{-13}	(75)
		CO ₂ , 5°C, drawn fiber	0.023×10^{-13}	(75)
		CO ₂ , 25°C, undrawn fiber	0.071×10^{-13}	(75)
	cm ³ (NPT) m ⁻² mil ⁻¹ atm ⁻¹	CO ₂	140	(7)
		O ₂	80	(7)
		N ₂	5	(7)

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Activation energy for permeation	—	CO ₂	—	(75)
Solubility coefficient	cm ³ (STP) cm ⁻³ Pa ⁻¹	CO ₂ , 5°C, undrawn fiber CO ₂ , 25°C, undrawn fiber CO ₂ , 5°C, drawn fiber CO ₂ , 25°C, undrawn fiber	9.97 × 10 ⁻⁶ 6.32 × 10 ⁻⁶ 12.8 × 10 ⁻⁶ 14.8 × 10 ⁻⁶	(75)
Thermal conductivity	W m ⁻¹ K ⁻¹	Zytel resins	0.25	—
Melt viscosity	Pa s	Newtonian (shear stress <30 kPa) [η] = 1.09 dl g ⁻¹ , M _n = 14,000 270°C 280°C 290°C	40–1,000 110 70 50	(1)
Speed of sound	m s ⁻¹	Longitudinal; density = 1.147 g cm ⁻³ Shear; density = 1.147 g cm ⁻³	2,710 1,120	(76)
Biodegradability, effective microorganisms	—	Wood Rotting Basidiomycetes	—	(7)
Heat of combustion	kJ kg ⁻¹	—	–31,400	(51)
Decomposition products	K	H ₂ O, CO ₂ , cyclopentanone, hydrocarbons H ₂ O, CO ₂ , NH ₃ , cyclic monomer, cyclopentanone, cyclopentylidinicyclopentanone, cyclopentylcyclopentanane, hexylamine, hexamethyleneimine, hexamethylene diamine	583–653 578	(77) (78)
Cross-linking, G factor	mol J ⁻¹	Electron beam/ γ irradiation	0.50	(79)
Gas evolution, G factor	mol J ⁻¹	—	0.70	(79)
Water absorption	%	Zytel ASTM D 570 24 h immersion, 23°C Saturation, 23°C Annealed (Karl Fisher method)	1.2 8.5 7	(8) (1)
Solvent absorption	%	Ethanol, 20°C, saturation Butanol, 20°C, saturation Glycol, 20°C, saturation Methanol, 20°C, saturation Propanol, 20°C, saturation	9–12 4–8 2–10 9–14 9–12	(10)
Oxygen index	%	Zytel ASTM D 2863	28–31	(8)

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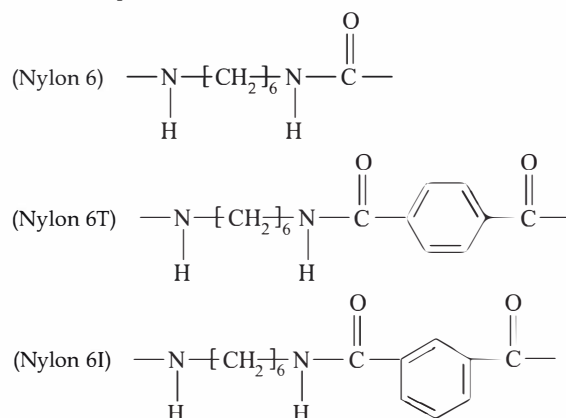
Nylon 6,6 copolymer

SHAW LING HSU

ACRONYM, ALTERNATIVE NAME, TRADE NAME PPA, polyphthalamide, Amodel (Amoco)

CLASS Aromatic polyamides; aromatic nylons

STRUCTURE As described in several articles and patents,^(1,2) this type of aromatic nylon resin is a polyamide consisting of varying portions of aliphatic and aromatic units. Hexamethylene diamine is the main aliphatic component, which may be augmented by various amounts of adipic acid. The main aromatic component is terephthalic acid, which may be augmented by lesser amounts of isophthalic acid. Depending on relative composition, Amodel (nylon 6,6 copolymer) resins can be regarded as co- and terpolymers consisting of repeat units of nylon 66, nylon 6T, and nylon 6I – poly(hexamethylene isophthalamide). The major potential difference of other aromatic nylons, such as Ultramid T from BASF, is the presence of the 6I component.^(1,2)



PROPERTIES OF SPECIAL INTEREST Because of the *p*-phenylene unit, extremely high melting temperature can be achieved. The degree of crystallinity, embrittlement, and transparency can all be controlled by adjusting the chemical composition (nylon 6I content).⁽³⁾ Dimensional stability in the presence of moisture. Exceptional mechanical properties (modulus > 2 × 10⁶ psi, strength), creep resistance, and flexural strength.

MAJOR APPLICATIONS High temperature applications, industrial and chemical processing equipment, bearings and gears, aerospace components, appliance and plumbing parts, electrical/electronics applications such as connectors, under-hood automobile applications, packaging.

Nylon 6,6 copolymer

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
NMR*	ppm	Range for amide proton peaks Range for methylene proton peaks	6–7 1–4	(4)
IR (characteristic absorption frequencies)	cm ⁻¹	Overall, the infrared spectrum greatly resembles those found for other polyamides N–H stretching Amide I Amide II Methylene stretching vibrations Methylene bending vibrations Other specific spectroscopic features can be linked to the presence of the aromatic component Vibrations assignable to para-disubstituted aromatic units Methylene/amide ratio is indicated by the ratio of the integrated band intensity at 3,000 cm ⁻¹ to that at 3,305 cm ⁻¹	3,305 1,627 1,545 3,000 1,400 862, 1,019, ~1,300, [†] 1,498	(5–12) — — — (7–9, 11–17) (7–9, 11–17) (2, 18) (9, 10, 19) (9, 20)
Melting temperature [‡]	K	Range (depending on composition) For Amoco products	543–593 585	(21)
Glass transition temperature	K	Depending on composition	400 362–408 399	(22) (22) (3)
Density	g cm ⁻³	—	1.27	(22)
Moisture uptake	%	23°C, saturation 23°C, 50% RH 23°C, 100% RH	62.55.9	(3)
Melt viscosity	poise	325°C	3,000	(22)
Degradation of aromatic polyamides by radiation		Plasma treatment can modify aromatic nylons reducing the relative concentration of amide units relative to that in untreated nylon 6,6 copolymer. These aromatic nylons can also be hydrolyzed in acid solutions.		(23)
Thermal conductivity	W m ⁻¹ K ⁻¹	40°C	0.24	(22)
Modulus	psi	Strength	>2 × 10 ⁶	—
Tensile strength	MPa	—	103–117	(22)
Yield stress	MPa	—	103–117	(22)

Nylon 6,6 copolymer

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Yield strain	%	—	3	(22)
Flexural modulus	MPa	—	3,500–3,800	(22)
Flexural strength	MPa	—	310	—
Degree of crystallinity	%	—	22–28	(22)
Deflection temperature	K	—	363–403	(22)
Solvents	Hexafluoroisopropanol (HFIP), hot sulfuric acid, hot phenol			(22)

*Both assignments fall into the range of peak positions listed for these groups in standard NMR tables.

†Broad features.

‡DSC melting curves associated with aromatic nylons have been reported for various compositions of the two components.

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Nylon 6,10

MELVIN I. KOHAN

ACRONYMS, TRADE NAMES PA 610, PA-610, Nylon-610, Amilan (Toray), Technyl D (Rhône Poulenc), Ultramid S (BASF)

CHEMICAL NAMES Poly(hexamethylene sebacamide), poly(hexamethylene decanoamide), poly(iminohexamethylene-iminosebacoyl), poly[imino-1,6-hexanediylimino(1,10-dioxo-1,10-decanediyl)] (CAS Registry No. 9008-66-6)

CLASS Aliphatic polyamides

STRUCTURE $-\text{[NH(CH}_2\text{)}_6\text{NHCO(CH}_2\text{)}_8\text{CO]}-$

This most often is not a pure homopolymer because the sebacic acid made from castor oil that is used in the commercial synthesis is not the 100% pure dibasic acid.

MAJOR APPLICATIONS Monofilament, hardware, industrial parts, and precision instruments.

PROPERTIES OF SPECIAL INTEREST Relatively low melting point; resistance to solvents, particularly hydrocarbons, and resistance to aqueous zinc chloride; low water absorption; stiffness; abrasion resistance; dimensional stability.

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Molecular weight	g mol^{-1}	Per amide group	141.21	—
		Per repeat unit	282.42	
Typical molecular weight range	g mol^{-1}	—	11,000–20,000	(1)
Typical polydispersity index, M_w/M_n (M_w/M_n)	—	—	2.0	—
Density	g cm^{-3}	Crystalline, α , triclinic	1.156	(2)
		Crystalline	1.152	(4)
		Typical injection molded	1.07–1.09	—
		Melt 270°C, 1 bar	0.913	(5)
		Melt 230–290°C	0.91–0.94	(1)
		Amorphous	1.05	(3)
		Amorphous	1.041	(4)
IR (characteristic absorption frequencies)	cm^{-1}	N-vic. CH_2 bend (α)	1,474	(6)
		CH_2 bend	1,466	
		CH_2 bend	1,437	
		CO-vic. CH_2 bend (α)	1,419	
		Amide III (?)	1,284	
		(α)	1,191	
		(γ , amorphous)	1,180	
		(amorphous)	1,133	

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
IR (characteristic absorption frequencies)		C-CO stretch (α or γ)	938	
		CH ₂ wag	730	
		Amide V (α)	689	
		Amide VI (α)	583	
NMR	—	—	—	(7)
Coefficient of linear thermal expansion	K ⁻¹	—	9.0×10^{-5}	—
Compressibility of the melt	Pa ⁻¹ (bar ⁻¹)	—	~ 5 ($\sim 5 \times 10^{-5}$)	(1)
PVT curves				(8)
Reduction temperature T^*	K	—	8,240	
Reduction pressure P^*	MPa	—	661	
Reduction volume V^*	cm ³ g ⁻¹	—	0.845	
Solvents	—	25°C	Concentrated sulfuric acid, <i>m</i> -cresol	—
		Redissolution, 156°C	Ethylene glycol	(9)
		Redissolution, 139°C	Propylene glycol	(9)
Mark-Houwink parameters: K and a	$K = \text{cm}^3 \text{g}^{-1}$ $a = \text{None}$	<i>m</i> -Cresol, 25°C, for $M_n = 8,000\text{--}24,000$	$K = 13,500$ $a = 0.96$	(10)
Polymers with which compatible	—	—	—	(22)
Unit cell dimensions	Å	α -Triclinic	$a = 4.95, b = 5.4, c = 22.4$	(2)
		β -Triclinic	$a = 4.9, b = 8.0, c = 22.4$	
Unit cell angles	Degrees	α -Triclinic	$\alpha = 49, \beta = 76.5, \gamma = 63.5$	(2)
		α -Triclinic	$\alpha = 90, \beta = 77, \gamma = 67.5$	
Units in cell	—	α -Triclinic	1	(2)
		β -Triclinic	2	
Degree of crystallinity	%	Range, injection molded	25–45	(11)
Heat of fusion (per repeat unit)	kJ mol ⁻¹ (kJ kg ⁻¹)	Crystalline, from ΔH_m , DTA	56.8 (201)	(12)
		Crystalline, from ΔH_m , DTA	54.6 (193)	(13)
		Crystalline, from sp. ht.	53.2 (188)	(14)
Entropy of fusion (per repeat unit)	J K ⁻¹ mol ⁻¹	Crystalline	110–114	(18)
Glass transition temperature	K	Dry, mech. loss peak	340	(15)
		Dry, flex. mod. vs. temp.	343	(15)
		Dry, DTA	315	(16)
		50% RH, mech. loss peak	313	(15)
		100% RH, mech. loss peak	283	(15)

Nylon 6,10

PROPERTY	UNITS	CONDITIONS	VALUE		REFERENCE
Melting point	K	X-ray	500		(17)
		DTA			(17)
		Start	494		
		Peak	497		
		End	499		
		Equilibrium	≥510		(29)
			Range	Average	
		Fisher-Johns	489-496	492	(17)
Heat capacity (per repeat unit)	J K ⁻¹ mol ⁻¹	Capillary	485-494	490	(17)
		Köfler hot stage	485-503	493	(17)
		—	502		(19)
		—			
Deflection temperature	K	ASTM D 648 = DIN			(20, 21)
		53461 = ISO 75			
		Dry			
		455 kPa	430-448		
		1,820 kPa	339		
		50% RH			
Tensile properties, ASTM D 638 = DIN 53455 = ISO 527	MPa	455 kPa	433		
		1,820 kPa	333		
		—			
		—			
Tensile modulus	MPa	23°C			(20, 21)
		Dry	2,400		
		50% RH	1,500		
		—			
Tensile strength	MPa	−40°C			(20, 21)
		Dry	83		
		50% RH	83		
		—			
Yield stress	MPa	23°C			
		Dry	59		
		50% RH	49		
		—			
Tensile properties, ASTM D 638 = DIN 53455 = ISO 527	MPa	77°C			
		Dry	37		
		50% RH	37		
		—			
Yield stress	MPa	−40°C			(20, 21)
		Dry	83		
		50% RH	83		
		—			
Tensile properties, ASTM D 638 = DIN 53455 = ISO 527	MPa	23°C			
		Dry	60		
		50% RH	50		
		—			
Yield stress	MPa	77°C			
		Dry	37		
		50% RH	37		
		—			

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Yield strain $(L/L_0)_y$	%	−40°C		(20, 21)
		Dry	10	
		50% RH	13	
		23°C		
		Dry	10	
		50% RH	30	
Maximum extensibility $(L/L_0)_t$	%	77°C		(20, 21)
		Dry	30	
		50% RH	—	
		−40°C		
		Dry	20	
		50% RH	30	
Flexural modulus	MPa	23°C		(20, 21)
		Dry	70–100	
		50% RH	≥150	
		77°C		
		Dry	300	
		50% RH	—	
Bulk modulus	MPa	ASTM D 790 = DIN 53457 = ISO 178		(24)
		−40°C		
		Dry	2,240	
		50% RH	2,520	
		23°C		
		Dry	2,000	
Shear strength	MPa	50% RH	1,100	(21)
		100% RH	690	
Impact strength (cf. ASTM D 256, DIN 53453, ISO 179)	J m^{-1}	77°C, dry	480	(20, 21)
		25°C	2,300	
	kJ m^{-2}	ASTM D 732, 23°C, dry	58	
		Notched Izod, 23°C		
Hardness	J m^{-1}	Dry	50	(21)
		50% RH	200	
	kJ m^{-2}	Charpy, 20°C		
		Dry	4–10	
Poisson ratio	—	65% RH, 4 months	13–15	(5)
		20°C, moldings	0.3–0.4	
Poisson ratio	—	100°C	0.47	(5)
		Melt	0.50	

Nylon 6,10

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Abrasion resistance, Taber	mg kHz ⁻¹	C17 wheel, 1 kg	5–6	(21)
Index of refraction	—	25°C, molded, undrawn	1.532	(11)
		Isotropic	1.52	
		Parallel	1.57	
		Perpendicular	1.52	
Dielectric constant	—	ASTM D 150, IEC 250		
		Dry		(21)
		50–100 Hz	3.9	
		1 kHz	3.6	
		1 MHz	3.3	
		–30, 0°C; 100 Hz–1 GHz	3.0	(5)*
		30°C		(5)
		100 Hz–1 kHz	3.2	
		1 MHz–1 GHz	3.0	
		60°C		(5)
		100 Hz	4.6	
		1 kHz	4.2	
		1 MHz	3.4	
		1 GHz	3.0	
		90°C		(5)
		100 Hz	13	
		1 kHz	10.5	
		1 MHz	5.2	
		1 GHz	3.1	
		20°C, 65% RH		(5)
		100 Hz	6.5	
		1 kHz	5.4	
		1 MHz	3.5	
		1 GHz	3.0	
Dissipation factor, dielectric loss	—	ASTM D 150, IEC 250		
		Dry		(21)
		50–100 Hz	0.04	
		1 kHz–1 MHz	0.03	
		–30°C		(5)*
		100 Hz	0.012	
		1 kHz	0.011	
		1 MHz	0.015	
		1 GHz	0.006	
		0°C		(5)
		100 Hz–1 kHz	0.013	
		1 MHz	0.017	
		1 GHz	0.010	

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Dissipation factor, dielectric loss	—	30°C		(5)
		100 Hz	0.010	
		1 kHz	0.015	
		1 MHz	0.021	
		1 GHz	0.013	
		60°C		(5)
		100 Hz	0.090	
		1 kHz	0.065	
		1 MHz	0.054	
		1 GHz	0.025	
		90°C		(5)
		100 Hz	0.250	
		1 kHz	0.170	
		1 MHz	0.190	
		1 GHz	0.035	
		20°C; 65% RH		(5)
Volume resistivity	ohm cm	ASTM D 257, IEC 93		
		Dry		(5, 21)
		20°C	10^{15}	
		60°C	5×10^{11}	
		100°C	5×10^8	
		20°C		(5)
Surface tension	mN m ⁻¹	50% RH	2×10^{12}	
		100% RH	3×10^{10}	
Surface tension	mN m ⁻¹	Melt, 265°C	37	(23)
Thermal conductivity	W m ⁻¹ K ⁻¹	—	0.23	(21)
		Amorphous, moist, 30°C	0.35	(24, 25)
		Dependence on pressure, $\lambda(25 \text{ kbar})/\lambda(\text{atm. pressure}); 25^\circ\text{C}$	1.90	(24, 25)
Melt viscosity	Pa s	Commercial injection molding grade resin, 280°C		(26)
		10 s^{-1}	37	
		10^2 s^{-1}	34	
		10^3 s^{-1}	27	
		10^4 s^{-1}	14	
Activation energy of viscous flow	kJ mol ⁻¹	—	60	(27)
Coefficient of friction	—	Thrust washer, 275 kPa, 0.25 m s ⁻¹		(28)
		Static	0.23	
		Dynamic	0.31	

Nylon 6,10

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Limiting PV against steel	kPa m s ⁻¹	0.5 m s ⁻¹	70	(28)
Water absorption	%	50% RH	1.4–1.5	—
		100% RH	3.3 ± 0.3	(5)
Solvent absorption	%	Ethanol, 20°C, saturation	8–13	(5)
		Butanol, 20°C, saturation	8–12	
		Glycol, 20°C, saturation	2–4	
		Methanol, 20°C, saturation	16	
		Propanol, 20°C, saturation	10	
Oxygen index	%	ASTM D 2863, dry	24	(5)

*Moisture content unspecified, but data indicate dry specimens.

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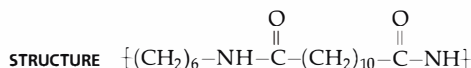
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Nylon 6,12

GUS G. PETERSON AND W. BROOKE ZHAO

ALTERNATIVE NAMES Poly[imino-1,6-hexanediylimino(1,12-dioxo-1,12-dedecanediyl)]

CLASS Aliphatic polyamides



MAJOR APPLICATIONS Engineering resin

PROPERTIES OF SPECIAL INTEREST Low water absorption compared to Nylon 6,6

PREPARATIVE TECHNIQUES Polycondensation of hexamethylenediamine and dodecanedioic acid

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Molecular weight (of repeat unit)	g mol^{-1}	Size-exclusion chromatography	$25,700 \pm 700$	(1)
IR (characteristic absorption frequencies)	cm^{-1}	N—H stretching C=O stretching (amide I band)	3,050 1,650–1,634	(2)
NMR (15N)	ppm	32°C 36°C 42°C 49°C 56°C	119.8 119.8 119.8 119.7 119.6	(3)
Thermal expansion coefficient	K^{-1}	Linear	9×10^{-5}	(2)
Density	g cm^{-3}	—	1.06	(4)
Common solvents	Phenols, formic acid, chloral hydrate, fluorinated alcohols, mineral acids			(2)
Contact angle	Degrees	<i>c</i> -Hex <i>i</i> -Oct	113.9 ± 1.0 109.0 ± 0.8	(5)
Equilibrium heats of fusion ΔH_f^0	kJ mol^{-1}	—	80.1	(6)
Glass transition temperature T_g	K	—	319	(6)
Melting temperature T_m	K	—	520–480	(6)

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Heat capacity	$\text{kJ K}^{-1} \text{mol}^{-1}$	230°C 300°C 400°C 600°C	0.382 0.494 0.771 0.981	(7)
Deflection temperature	K	0.455 MPa 1.82 MPa	453 363	(2)
Brittleness temperature	K	—	164	(2)
Specific heat	$\text{kJ K}^{-1} \text{mol}^{-1}$	—	0.525	(2)
Tensile strength	MPa	—	60.7	(2)
Yield stress	MPa	—	51.0	(2)
Elongation at break	%	—	≥ 300	(2)
Elongation at yield	%	—	25	(2)
Shear strength	MPa	Dry	55.8	(2)
Flexural modulus	MPa	—	1,241	(2)
Izod impact strength	J m^{-1}	—	75	(2)
Dielectric constant ϵ'	—	—	5.3×10^3	(2)
Volume resistivity	ohm cm	—	10^{13}	(4)
Dissipation factor	—	1,000 Hz	0.15	(2)
Dispersion force component of surface free energy γ_s^d	mJ m^{-2}	—	62 ± 9	(5)
Nondispersive interaction free energy between solid and water I_{SM}^n	mJ m^{-2}	—	30.7 ± 0.4	(5)
Polar surface free energy γ_s^p	mJ m^{-2}	—	4.7	(5)
Surface free energy γ_s	mJ m^{-2}	—	67	(5)
Thermal conductivity	$\text{W m}^{-1} \text{K}^{-1}$	—	0.22	(2)
Intrinsic viscosity	dL g^{-1}	—	1.45	(8)
Water absorption	%	At saturation	3.0	(2)
Flammability, oxygen index	—	—	28	(2)

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Nylon 11

GEORGE APGAR

ACRONYMS, TRADE NAME Polyamide 11, PA-11, Rilsan[®] B (Elf Atochem)

CLASS Aliphatic polyamides

STRUCTURE $[-C(=O)-(CH_2)_{10}-NH-]$

MAJOR APPLICATIONS Tubing, hoses, and pipes for automotive, trucking, industrial, and petroleum production applications. Examples are heavy truck airbrake tubing, automotive fuel lines, and submarine flexible pipes for offshore oil production. Thermoplastic powder coatings for industrial, transportation, and retail items are prepared in a Nylon 11 base. Nylon 11 has been used in a variety of food-contact applications, including sausage casing, beverage tubing, and reusable kitchen devices.

PROPERTIES OF SPECIAL INTEREST Nylon 11 has low moisture absorption relative to other nylons. Specific gravity is also low. Chemical resistance to hydrolytic reagents is unusually good for a polyamide. Modulus is low, which provides superior impact properties at both ambient and subambient temperatures.

PREPARATIVE TECHNIQUES Nylon 11 is prepared by a condensation polymerization reaction. The commercial monomer is 11, aminoundecanoic acid. This amino acid is unique among the nylon monomers because it is made from castor oil, a renewable, agricultural raw material. The 18-carbon ricinoleic acid is thermally cracked to 7-carbon and 11-carbon fractions. The 11-carbon portion has an omega unsaturation, which is hydrobrominated then aminated to the amino acid monomer.⁽¹⁾

PROPERTY*	UNITS	CONDITIONS	VALUE	REFERENCE
Common form	—	—	α , triclinic	(2)
Unit cell dimensions	Å	<i>a</i> axis	4.9	(2)
		<i>b</i> axis	5.4	
		<i>c</i> axis	14.9	
Angles	Degrees	Alpha	40	(2)
		Beta	77	
		Gamma	63	
Density, crystalline	g cm^{-3}	—	1.15	(2)
Density, amorphous	g cm^{-3}	25% crystallinity is typical after melt processing	1.01	(2)
Water absorption	wt%	Equilibration at		(2)
		23°C, 65% RH	1.1	
		23°C, 100% RH	1.9	
		100°C, 65% RH	3.0	

Nylon 11

PROPERTY*	UNITS	CONDITIONS	VALUE	REFERENCE
Heat of fusion	J g ⁻¹	24% crystallinity	39	(2)
Specific heat	J g ⁻¹ K ⁻¹	23°C 250°C	1.752.6	(2)
Glass transition temperature	K	—	315	(2)
Thermal conductivity	W m ⁻¹ K ⁻¹	—	0.19	(3)
Mark-Houwink parameters: <i>K</i> and <i>a</i>	<i>K</i> = ml g ⁻¹ <i>a</i> = None	For PA-11; mol. wt. = 1.8–9 × 10 ⁴ at 30°C in <i>m</i> -Cresol	<i>K</i> = 91 <i>a</i> = 0.69	(4)
Melt viscosity	Poise	For commercial grades of PA-11; 240°C; 500 s ⁻¹ shear rate	1,000–7,000	(5)
Dielectric constant	—	Dry, 10 ⁶ Hz	3.1	(6)
Dissipation factor	—	Dry, 10 ⁶ Hz	0.04	(6)
Specific gravity	—	23°C Unmodified Plasticized 43% glass	1.03 1.05 1.36	(2)
Melting point	K	Unmodified Plasticized 43% glass	461 457 461	(2)
Yield stress	MPa	23°C Unmodified Plasticized	36 21	(2)
Yield elongation	%	23°C Unmodified Plasticized	22 26	(2)
Break stress	MPa	–40°C Unmodified Plasticized 23°C Unmodified Plasticized 43% glass 80°C Unmodified Plasticized	72 76 68 62 145 66 54	(2)

Nylon 11

PROPERTY*	UNITS	CONDITIONS	VALUE	REFERENCE
Break elongation	%	-40°C		(2)
		Unmodified	160	
		Plasticized	220	
		23°C		
		Unmodified	360	
		Plasticized	380	
		43% glass	8	
		80°C		
Flexural modulus	MPa	-40°C		(2)
		Unmodified	1,586	
		Plasticized	2,275	
		23°C		
		Unmodified	1,269	
		Plasticized	310	
		43% glass	8,480	
		80°C		
Izod impact strength	J m ⁻¹	-40°C		(2)
		Unmodified	27	
		Plasticized	21	
		23°C		
		Unmodified	99	
		Plasticized	No break	
		43% glass	247	
		80°C		
Deflection temperature	K	Unmodified	320	(2)
		Plasticized	313	
		43% glass	452	
Rockwell hardness	—	23°C		(2)
		Unmodified	R108	
		Plasticized	R75	
		43% glass	R111	
Hardness	Shore D values	23°C		(2)
		Unmodified	72	
		Plasticized	63	

Nylon 11

PROPERTY*	UNITS	CONDITIONS	VALUE	REFERENCE
Coefficient of linear thermal expansion	$K^{-1} (\times 10^{-5})$	-30 to 50°C		(2)
		Unmodified	8,5	
		Plasticized	11	
		43% glass	7	
		50-120°C		
		Unmodified	15	
Volume resistivity	ohm cm	500 VDC; 20°C		(2)
		Unmodified	1,014	
		Plasticized	1,011	
		43% glass	1,014	
Surface resistivity	ohm	20°C		(2)
		Unmodified	1,014	
		Plasticized	1,011	
		43% glass	1,014	
Dielectric strength	$kV mm^{-1}$	20°C		(2)
		Unmodified	30	
		Plasticized	24	
		43% glass	45	

*All properties measured in a dry, as-molded state.

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Nylon 12

H. ULF W. ROHDE-LIEBENAU

ACRONYMS, TRADE NAMES PA 12, polyamide 12, polydodecanolactam, polylauro lactam; Daiamid[®] (Daicel Chemical Industries); Grilamid[®] (EMS Chemie); Rilsan[®] A (Elf Atochem); UBE Nylon 12[®] (UBE Industries); Vestamid[®] (Creanova)

CLASS Aliphatic polyamides

STRUCTURE $-\text{[NH}_2-(\text{CH}_2)_{11}-\text{CO}]_p-$

PROPERTIES OF SPECIAL INTEREST Hydrolytic polycondensation at 260–300°C. Very low monomer content in melt-equilibrium. Activated anionic polymerization = monomer casting (small market volume). PA 12 crystallizes in pseudo-hexagonal modification. Combination of typical nylon and polyolefin properties. Low moisture absorption and density, chemical resistance similar to other nylons, not sensitive to stress cracking. Good to excellent impact strength, in dry state or at low temperatures. Engineering plastic, can be modified by glass or carbon fiber reinforcement, plasticizer, or other additives. PA 12 copolymers with PTHF: polyether block amides (PEBA)—see below.⁽¹⁾

MAJOR APPLICATIONS Multiplicity of applications in technical engineering, especially in automotive and electrical industries. Antistatic parts. Precision molding. Sports and leisure goods. Coatings by extrusion, fluidized bed, or electrostatic process.

GENERAL INFORMATION Most properties were determined by relevant ISO and IEC standards in accordance with CAMPUS[®]. Three grades from the vast range of grades were selected: (1) unmodified extrusion, (2) with ~13% plasticizer, and (3) 30% glass fiber modified grade. (See ISO 1874-2 for a list of relevant standards.)

PROPERTIES	UNIT	CONDITIONS	VALUE			REFERENCE
			Unmodified	Plasticized	30% glass fiber	
Density	g cm ⁻³	Standard: ISO 1183				
		At 23°C	1.01–1.02	1.03	1.24	(2–4)
		Annealed at 160°C	1.028	Monomer casting	—	(2–4)
		At 260°C (melt)	~0.86	~0.88	~1.04	(5)
Moisture absorption	%	Standard: DIN 53495				(2–4)
		23°C, 50% RH	0.8	0.7	0.4–0.5	
		23°C, immersed	1.5	1.4	1.1	
Melting range	K	Polarization microscopy	448–453			(2–4)
Heat deflection temperature	K	Standard: ISO 75; load = 0.45 MPa	388	363	448	(2–4)

Nylon 12

PROPERTIES	UNIT	CONDITIONS	VALUE			REFERENCE
			Unmodified	Plasticized	30% glass fiber	
Vicat softening point	K	Standard: ISO 306; load = 10 N	443	433	448	(2-4)
Glass transition temperature	K	Standard: ISO 537; $\tan \delta$ by torsional pendulum Dry as molded 50% RH (=0.7% H ₂ O)	328 318			(2-4)
Thermal expansion coefficient	K ⁻¹ ($\times 10^{-4}$)	Standard: DIN 53752; for 23–80°C In flow direction Perpendicular direction	1.5 1.1	1.8 1.5	0.6 —	(2-4)
Specific heat	J g ⁻¹ K ⁻¹	Solid (23–60°C) Melt (250°C)	2.0 2.9	— 3.0	1.6 2.5	(3)
Heat of fusion	J g ⁻¹	—	65–75 ^(a)	—	35–40 ^(b)	(3)
Thermal conductivity	W m ⁻¹ K ⁻¹	20–100°C	0.24	0.23	0.29	(3)
Melt volume index	ml (10 min) ⁻¹	275°C (5 kg load) ⁻¹	~36	~60	~30	(5)
Maximum use temperature	K	Standard: UL 746B	358	353	378	(UL 746)
Flammability	Most PA 12 grades are slow burning (HB acc. UL 94), but there are self-extinguishing grades					(UL 94)
Oxygen index	%	Unmodified PA 12	21–22			(5)
Tensile modulus	MPa	Standard: ISO 527; equilibrated to 50% RH	1,450	400	6,500	(2-4)
Yield stress	MPa	Standard: ISO 527; equilibrated to 50% RH	46	26	130	(2-4)
Strain at yield	%	Standard: ISO 527; equilibrated to 50% RH	5	30	5	(2-4)
Strain at break	%	Standard: ISO 527; equilibrated to 50% RH	>200	>200	5–6	(2-4)
Notched impact strength (Izod)	kJ m ⁻²	Standard: ISO 180/1A; equilibrated to 50% RH At 23°C At –30°C	20 7	No break 6	24 20	(2-4)

Nylon 12

PROPERTIES	UNIT	CONDITIONS	VALUE			REFERENCE
			Unmodified	Plasticized	30% glass fiber	
Notched impact strength (Charpy)	kJ m ⁻²	Standard: ISO 179; equilibrated to 50% RH	A ^(c)	B ^(d)		(2-4)
		At 23°C	6	20		
		At -30°C	5	7		
Dielectric constant ε'	—	Standard: IEC 250; 1 MHz; equilibrated to 50% RH	3.0	3.8	3.4	(4)
Dielectric loss ε''	—	Standard: IEC 250; 1 MHz; equilibrated to 50% RH	280 × 10 ⁻⁴	1,500 × 10 ⁻⁴	230 × 10 ⁻⁴	(4)
Dielectric strength	kV mm ⁻¹	Standard: IEC 243; equilibrated to 50% RH	26	31	44	(4)
Surface resistivity R _{OA}	ohm	Standard: IEC 93; equilibrated to 50% RH	10 ¹³	10 ¹²	10 ¹³	(4)
Volume resistivity	ohm cm	Standard: IEC 93; equilibrated to 50% RH	10 ¹⁵	10 ¹²	10 ¹⁵	(4)
Comp. tracking index	—	Standard: IEC 112; equilibrated to 50% RH	600	600	>600	(4)
Molecular mass	g mol ⁻¹	—	M _n = 1.4-3.0 (×10 ⁴) M _w = 3.5-10.5 (×10 ⁴)			(6-8)
Typical polydispersity index (M _w /M _n)	—	—	2.5-3.5			(6-8)
Mark-Houwink parameters: K and a	K = ml g ⁻¹ a = None	—	K = 524 × 10 ⁻⁴ a = 0.73			(6-8)
Degree of crystallinity	%	Cooled After annealing at 150°C	~0.3 0.35-0.40			—
Unit cell dimensions	Pseudohexagonal gamma-modification with unit cell dimensions					(2, 3)
Lattice	—	—	Pseudohexagonal			(2, 3)
Unit cell content (number of repeat units)	—	—	4			(9)

Nylon 12

PROPERTIES	UNIT	CONDITIONS	VALUE			REFERENCE
			Unmodified	Plasticized	30% glass fiber	
Cell dimensions	nm	—	$a = 0.479, b = 3.19, c = 0.958$			(9)
Cell angle	Degrees	—	$\beta = 120$			(9)
Density (crystalline)	g cm^{-3}	Also unstable monoclinic α modification	1.106 ^(e)			(10)
Index of refraction n_D^{25}	—	Only film and thin quenched parts are transparent	1.52–1.53			(5)

^(a) Range = 160–195°C. ^(b) Range = 155–185°C.

^(c) A = low molecular weight/injection molding. ^(d) B = high molecular weight/extrusion.

^(e) Some sources give the crystalline density as 1.03 to 1.05 g cm^{-3} , which is too low. If one extrapolates data from reference (11) or if a parallel for nylon 12 is drawn to the line of density vs. crystallinity for nylon 11 from reference (12), then one can derive the approximate crystalline density of 1.10 g cm^{-3} .

Polyether block amides (PEBA) are internally plasticized by copolycondensation of PA 12 and PTHF block segments. The grades are differentiated by Shore hardness D as a measure of flexibility. In addition to typical PA 12 application ranges, PEBA are used for seals, gaskets and in medical devices. (Trade name of these grades of Elf Atochem is Pebax[®])

PROPERTY	UNITS	[STANDARD]/ CONDITIONS	SHORE D HARDNESS*				PA 12	REFERENCE
			35	47	55	62		
Density	g cm^{-3}	[ISO 1183]	1.01	1.02	1.03	1.03	1.01–1.02	(1–3)
Tensile modulus	MPa	[ISO 527]	—	120	230	370	1,450	(1–3)
Yield stress	MPa	[ISO 527]	—	—	—	24	47	(1–3)
Tensile strength	MPa	[ISO 527]	17	23	32	—	—	(1–3)
Strain at break	%	[ISO 527]	>200	>200	>200	>200	>200	(1–3)
Notched impact strength (Izod)	kJ m^{-2}	[ISO 180/1A] At 23°C At –30°C	No break No break	No break No break	No break 22	No break 8	20 7	(1–3)
Heat deflection temperature	K	[ISO 75]; load 0.45 MPa	328	338	363	373	393	(1–3)
Vicat softening point	K	[ISO 306]; load 10 N	398	413	433	438	443	(1–3)

*Standard: ISO 868.

Suppliers

EMS Chemie AG, Domat, Switzerland
 Elf Atochem S.A., Paris, France
 UBE Industries, Tokyo, Japan
 Creanova GmbH, Division of Degussa-Hüls AG., Marl, Germany

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A. PRASAD

ACRONYMS LDPE, branched PE, high-pressure PE

CLASS Poly(α -olefin)

STRUCTURE $-\text{[CH}_2-\text{CH}_2\text{]}_n-$

INTRODUCTION LDPE is produced under high pressure (82–276 MPa) and high temperature (405–605 K) with a free radical initiator (such as peroxides and oxygen) and contains some long chain branches (LCB), which could be as long as chain backbones,^(1,2) and short chain branches (SCB).⁽³⁾ It is produced by either a tubular or a stirred autoclave reactor.⁽⁴⁾ The autoclave process can produce LDPE resins having a wide range of molecular weight distribution (MWD) and less LCB in comparison with a tubular reactor.⁽⁴⁾ Long chain branching has a strong influence on MWD, and hence on resin properties, such as processibility, melt strength, and film optical properties.⁽⁴⁾ SCBs disrupt chain packing and are principally responsible for lowering the melting temperature and the crystal density for hydrocarbon polymers. LDPE is commercially available in a wide variety of molecular weight, MWD, SCB, and LCB contents, and density ranges.^(4–6)

Thermal and mechanical properties of semicrystalline polymers are strongly dependent on MW, MWD, branching content, and density.^(5,7,8) Controlled variations in these structural parameters result in a broad family of products with wide differences in thermal and mechanical properties. Shear modified LDPE samples are also available commercially.^(9,10) The deliberate shearing of polymer melt results in a reduction in melt viscosity and elasticity without significant change in MW.⁽¹¹⁾ These reversible changes are advantageous for molding and extrusion and also result in film with better optical properties.^(9,10,12) Shear modified LDPEs show vastly different crystallization rates.⁽¹²⁾ The properties shown in the following table are given in ranges because of their dependence on molecular structure and are intended to represent best published examples of most commonly used commercial grades of LDPE for blown film, molding, and extrusion coating applications. Table 3 contains properties of tubular blown films.

MAJOR APPLICATIONS Major applications include blown film for bags and packaging; extrusion coatings for paper, metal, and glass; and injection molding for can lids, toys, and pails. Other applications include blow molding (squeeze bottles), rotomolding and wire and cable coatings, carpet backing, and foam for packaging material. There is considerable use of blends of LDPE with high-density polyethylene (HDPE) and linear low-density polyethylene (LLDPE) in a wide variety of applications. These blends are deliberately excluded in the data presented below.

PROPERTIES OF SPECIAL INTEREST LDPE has a good balance of mechanical and optical properties with easy processibility and low cost. It can be fabricated by many different methods for a broad range of applications. Special properties of interest include: optical clarity, flexibility, toughness, high impact strength, good heat seal, low brittleness temperature, good chemical resistance to aqueous solvents, and good electrical properties. LDPE may not be suitable for applications that require

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high stiffness and high tensile strength. Other limitations include: poor resistance to oxidizing agents, aliphatic solvents, aromatic solvents, polar liquids, chlorinated solvents, low softening point, poor scratch resistance, poor gas and moisture permeability, and relatively lower stress-crack resistance when compared to other types of polyethylene. LDPE undergoes thermal degradation at high temperatures and chain extension under shear conditions.

MAJOR SUPPLIERS Equistar Chemicals LP., Dow Chemical Co., Chevron Chemical Co., Westlake Plastics Co., Du Pont Co., Exxon Chemical Co., Eastman Chemical Co., Union Carbide Corp., Mobil Polymers, Rexene Corp., Novacor Chemicals, Inc.

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Type of branching	—	FTIR, NMR	Methyl, ethyl, butyl, amyl and longer branches	(13-15)
Type of unsaturation	%	FTIR		(16)
		Vinylidene	80	
		Vinyl	10	
		<i>Trans</i>	10	
Degree of SCB, commercial grades	Methyl/1,000 carbon	FTIR, NMR	10-33	(13-15)
Typical M_w range, commercial grades	g mol^{-1}	GPC	$3-40 \times 10^4$	(5, 16)
Typical polydispersity index (M_w/M_n)	—	GPC, strongly influenced by the amount of LCB	4-30	(17-19)
IR (characteristic absorption frequencies)	cm^{-1}	Thin film sample at room temperature	See table below	(14, 15, 20)

Characteristic frequencies of crystalline LDPE*

Wave number	Intensity	Assignments
720	Very strong	CH ₂ rocking
731	Very strong	CH ₂ rocking
888	Very weak	Vinylidene groups
890	Very weak	CH ₃ rocking
908	Medium	Terminal vinyl groups
964	Very weak	<i>Trans</i> double bond
990	Weak	Terminal vinyl groups
1,050	Very weak	CH ₂ twisting
1,176	Very weak	CH ₂ wagging
1,375	Weak-medium	CH ₃ symmetrical bending
1,457	Very weak	CH ₃ asymmetrical bending
1,463	Very strong	CH ₂ bending

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Characteristic frequencies of crystalline LDPE*

Wave number	Intensity	Assignments
1,473	Very strong	CH ₂ bending
2,850	Very strong	CH ₂ symmetrical stretching
2,857	Very strong	CH ₂ symmetrical stretching
2,874	Weak	CH ₃ symmetrical stretching
2,899	Very strong	CH ₂ asymmetrical stretching
2,924	Very strong	CH ₂ asymmetrical stretching
2,960	Weak	CH ₃ asymmetrical stretching

*Observed in the infrared spectra and band assignments.

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Linear thermal expansion coefficient	K ⁻¹ (×10 ⁻⁵)	D 696	10.0–51.0	(21–23)
		Temperature range = 238–423 K	See table below	(5, 16)

Temp. (K)	Coefficient of expansion (× 10 ⁻⁵)	
	Linear	Cubical
238	10.0	30.0
273	18.3	55.0
293	23.7	71.0
313	29.0	87.0
333	33.7	101.0
353	40.3	121.0
373	46.6	140.0
383	51.0	153.0
388–423	25.0	75.0

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Density (amorphous)	g cm ⁻³	At 298 K, extrapolated from melt temperature	0.855	(24, 25)
Solvents	—	368 K	Decalin, toluene	(26, 27)
		369 K	Xylene	
		371 K	Tetralin	
		341 K	Cyclohexene	
		374 K	<i>n</i> -Tetracosane	
Nonsolvents	—	359 K	Methylene chloride	(27)
		361 K	<i>o</i> -Dichloro benzene	
		366 K	1,2-Dichloropropane	

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Solubility parameter	(MPa) ^{1/2}	<i>n</i> -Tetracosane, 374 K	15.20	(27)
		Cyclohexene, 341 K	17.10	(27)
		<i>n</i> -Heptane, 359 K	14.57	(27)
		<i>n</i> -Octane, 361 K	14.50	(27)
		<i>n</i> -Hexane, 359 K	12.46	(27)
		<i>n</i> -Pentane, 361 K	12.52	(27)
		Chloroform, 350 K	16.00	(27)
		Carbon tetrachloride, 346 K	14.77	(27)
		Tetrachloroethylene, 346 K	15.69	(27)
		Chlorobenzene, 349 K	18.13	(27)
		<i>o</i> -Dichlorobenzene, 361 K	18.62	(27)
		Methylene chloride, 359 K	13.75	(27)
		See also the other references for more data	—	(27, 28–31)
Theta temperature θ	K	Bis(2-ethylhexyl)adipate	418–443	(28)
		Bis(2-ethylhexyl)sebacate	423	
Flory interaction parameter χ	—	<i>n</i> -Tetracosane, 374 K	–0.09	(27)
		Cyclohexene, 341 K	–0.03	(27)
		<i>n</i> -Heptane, 359 K	0.13	(27)
		<i>n</i> -Octane, 361 K	0.18	(27)
		<i>n</i> -Octane, 393 K	0.31	(29)
		<i>n</i> -Octane, 418 K	0.30	(29)
		<i>n</i> -Hexane, 359 K	0.23	(27)
		<i>n</i> -Pentane, 361 K	0.35	(27)
		Toluene, 393 K	0.34	(29)
		Xylene, 350 K	0.51	(29)
		<i>m</i> -Xylene, 393 K	0.29	(29)
		<i>p</i> -Xylene, 393 K	0.27	(29)
		Chloroform, 350 K	0.25	(27)
		Tetrachloroethylene, 346 K	–0.05	(27)
		Chlorobenzene, 349 K	0.04	(27)
		<i>o</i> -Dichlorobenzene, 361 K	0.41	(27)
		Methylene chloride, 359 K	0.60	(27)
		Carbon tetrachloride, 346 K	0.01	(27)
		See also the other references for more data	—	(27–29)
Second virial coefficient A_2	mol cm ³ g ^{–2}	Tetralin, 334 K		(32, 33)
		$M_w = 5.73 \times 10^5$	0.92×10^{-4}	
		$M_w = 1.98 \times 10^6$	0.84×10^{-4}	

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Mark-Houwink parameters: K and a	$K = \text{ml g}^{-1}$ $a = \text{None}$	Should be used for approximate MW values only because LDPE contains long-chain branching Decalin, 342 K p -Xylene, 347 K Xylene, 353 K	— $K = 3.87 \times 10^{-4}$, $a = 0.78$ $K = 1.05 \times 10^{-3}$, $a = 0.63$ $K = 1.35 \times 10^{-4}$, $a = 0.63$	(32–36) (36) (33) (34)
Characteristics ratio $\langle r^2 \rangle / nl^2$	—	Tetralin, 334 K	7.26, 7.58	(32)
Crystallographic data	Å	Wide-angle X-ray (WAXD)	See table below	(37–40)

Unit cell information

Lattice	Space group	Unit cell dimensions (Å)			Monomers per unit cell	Reference
		a	b	c		
Orthorhombic	Pnam	7.40	4.93	2.534	2	(37)
		7.36	4.92	—	—	(38)
		7.51	4.97	—	—	(39)
Monoclinic	C2/m	8.09	2.53	4.79	2	(40)

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Crystallinity	%	DSC	33–53	(41–48)
Heat of fusion (per repeat unit)	kJ mol^{-1}	DSC	1.37–2.18	(41–48)
Density	g cm^{-3}	Commercial resins, ASTM D 1505	0.910–0.935	(4–6)
		Unit cell, 100% crystalline	1.00	(37)
		Unit cell, 100% crystalline	1.014	(38)
Lamellae thickness	Å	Raman longitudinal acoustic mode (LAM), various crystallization conditions used	See Table 1	(16, 48)
Crystal phase structure	%	LAM	See Table 1	(48)
Crystal orientation and birefringence	—	WAXD and infrared diachroism	See Table 2	(58)
Melting temperature	K	DSC, peak endotherms	378–388	(5, 6, 41, 44)

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Glass transition temperature	K	DMA, TMA	140–170 (See also transition and relaxation temperature table below)	(45–47)
Transition and relaxation temperatures; and activation energy*	—	DMA	See table below	(16, 45–49)

*The transitions and relaxation temperatures associated with amorphous regions are designated as α , β , γ , etc. in descending temperature order. Several conflicting interpretations and values have been given regarding the origin and molecular nature of the transitions in LDPE (see references 45 to 49). It is believed that the values of T_a depends on crystallite thickness. The temperature of beta transition, T_β , does not depend on the crystallite thickness but rather the comonomer type and content. The γ transition is associated with glass transition. All transition values depend on the frequency of the DMA test. See references (46) and (47) for detailed discussions. The transition temperatures associated with peaks in dynamic loss listed in this table are given in ranges because of a wide range of values cited in the literature (for a specific examples see Table 1 below).

Transitions	Temperature range (K)	Approximate activation energy (kJ mol ⁻¹)
α	293–360	>420
β	233–280	160–200
γ	140–170	32–75

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Heat capacity (of repeat units)	kJ k ⁻¹ mol ⁻¹	At constant pressure and temperature of 298 K, (density = 0.921 g cm ⁻³)	1.6536 × 10 ⁻⁴	(50, 51)
		At other temperatures	—	(51)
Enthalpy (of repeat unit)	kJ mol ⁻¹	Calorimeter		(51)
		Temperature (K)		
		80	0.287	
		140	0.883	
		200	1.722	
		260	2.887	
		320	4.545	
		380	7.619	
		415	9.384	
Entropy (of repeat unit)	kJ k ⁻¹ mol ⁻¹	Calorimeter		(51)
		Temperature (K)		
		80	0.00586	
		140	0.0114	
		200	0.0164	
		260	0.0214	
		320	0.0273	
		380	0.0357	
		415	0.0406	

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Deflection temperature	K	D 648, at 273 K and 0.45 MPa	311–322	(23)
Heat distortion temperature	K	D 648, 455 KPa	313–323	(21)
Vicant softening point	K	D 1525	363–375	(5)
Tensile modulus	MPa	D 638	102–310	(5, 21, 52)
Compressive strength	MPa	D 695	18–25	(23)
Tensile yield strength	MPa	D 638	9–15	(5, 21, 52)
Elongation at break	%	D 638	100–800	(5, 21, 52)
Yield stress	MPa	D 638	6.2–11.5	(5, 21, 52)
Flexural modulus	MPa	D 790 at 298 K	240–330	(6, 21, 52)
Impact strength, notched Izod	J m ⁻¹	D 256A	No break	(6, 21, 52)
Hardness	Shore D	D 676	40–60	(5, 6, 21, 52)
Low-temperature brittleness F ₅₀	K	D 746	<197	(21, 52)
Refractive index	—	D 542, crystalline (value depends on density and chain branching)	1.5168–1.5260	(21, 53)
		Amorphous	1.49	(16, 54)
		Refractive index in melt	See table below	(54)
Specific volume	cm ³ g ⁻¹	Differential refractometer and dilatometer, Alathon 10	See table below	(54)
Specific refractivity	cm ³ g ⁻¹	Differential refractometer and dilatometer, Alathon 10	See table below	(54)

Temperature (K)	Specific volume (cm ³ g ⁻¹)	Refractive index	Refractivity (cm ³ g ⁻¹)
363.16	1.159	1.4801	0.3293
368.16	1.168	1.4736	0.3281
373.16	1.178	1.4693	0.3283
378.16	1.195	1.4630	0.3291
381.16	1.209	1.4575	0.3297
384.16	1.282	1.4510	0.3290
386.16	1.239	1.4432	0.3286
391.16	1.250	1.4392	0.3289
387.56	1.256	1.4368	0.3288

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Dielectric constant ϵ'	—	D 150 at 1 kHz Density (g cm^{-3}) 0.920 0.930 0.935	2.28 2.30 2.31	(5, 21, 55)
Loss factor, $\tan \delta$	—	Up to 100 MHz	10^{-4} – 10^{-3}	(5, 21)
Dielectric strength	Mv cm^{-1}	D 149, 283 K D 149, 373 K	7.0 2.0	(21, 55, 56)
Power factor	—	D 150 at 1 kHz	0.0003	(5)
Melt index	g (10 min)^{-1}	D 1238	0.2–50	(4, 6)
Flow activation energy: EH and E_V^*	kJ mol^{-1}	RMS, melt index = $\sim 1 \text{ g (10 min)}^{-1}$ density = $0.919\text{--}0.931 \text{ g cm}^{-3}$, temp. range = 423–483 K	$E_H = 61\text{--}67$ $E_V = 8\text{--}10.5$	(59)
Coefficient of sliding friction μ	—	D 1894, dynamic c.o.f. to stainless steel, melt index = $2 \text{ g (10 min)}^{-1}$ density = 0.915 g cm^{-3}	0.7	(57)
Sonic velocity	m s^{-1}	Blown films	See Table 2	(58)
Water absorption	%	D 570, 24 h	<0.02	(21)

*The horizontal shift factor reflects the temperature dependence of relaxation time, and the vertical shift factor reflects the temperature dependence of modulus.

Table 1. Morphological and relaxation properties of LDPE as a function of crystallization condition^{*(48)}

Condition	α -Relaxation	β -Relaxation	Crystallinity (%)	Crystallite thickness (Å)	% Crystal phase structure		
	(K, 3.5 Hz)	(K, 3.5 Hz)			α_c	α_a	α_b
Slow cooled	348	258	36	105	37	49	14
Cooled in air	323	258	—	82	—	—	—
Quenched 80°C	323	258	40	80	36	53	11
Quenched 40°C	278	—	—	70	—	—	—
Quenched 0°C	273	—	32	—	—	—	—
Quenched –120°C	270	—	29	65	38	49	13

* $M_w = 3.46 \times 10^5$, $M_w/M_n = 18.5$, total SCB/1,000 C = 10.6, LCB/1,000 C = 2.2.

Note: Compression molded specimens were rapidly quenched to the specified quenching temperatures. Relaxation temperatures ($\tan \delta$ peaks) were obtained on a DMA instrument at a heating scan rate of 1°C min^{-1} . Crystal phase structures were obtained by Raman LAM. The degree of crystallinity was determined from the heat of fusion data obtained on a DSC instrument.

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Table 2. Morphological properties and crystal orientation of LDPE (density 0.920 g cm^{-3}) blown tubular films⁽⁵⁸⁾

Thickness (μm)	Density (gcm^{-3})	Birefringence ($\times 10^3$)	Sonic velocity (m s^{-1})		Infrared diachroic ratio (at 730 cm^{-1})	X-ray angle (degree)			
			MD*	TD*		a-axis		b-axis	
						MD-TD*	ND-MD*	MD-TD*	ND-MD*
54	0.9182	-9.79	953	1,128	1.15	45-50	45-60	0	0
26	—	-8.23	870	1,003	0.88	45	45-60	0	0
23	0.9175	-3.07	852	998	1.13	70	60-70	0	0

*MD, TD, and ND refers to the machine, transverse, and normal direction of a blown film sample.

Table 3. Blown film properties of high clarity grade LDPE*

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Melt index	g (10 min)^{-1}	D 1238	2.0	(66)
Density	g cm^{-3}	D 1505	0.924	(66)
Peak melting point	K	DSC, $10^\circ\text{C min}^{-1}$ cooling and heating rate	382.5	(66)
Heat of fusion	kJ mol^{-1}	DSC, $10^\circ\text{C min}^{-1}$ cooling and heating rate	1.50	(66)
M_w	g mol^{-1}	GPC, 408 K in 1,2,4-trichlorobenzene	79,200	(66)
M_w/M_n	—	GPC	3.8	(66)
Total haze	%	D 1003	5.2	(66)
Gloss, 45°D	Units	D 2457	71	(66)
Narrow angle scattering	%	D 1746	72	(66)
Modulus, 1% secant	MPa	D 882, MD D 882, TD	200 240	(66)
Dart impact (per mil)	g	D 1709, D 4272	74	(66)
Elmendorf tear	g	D 1922, MD D 1922, TD	360 220	(65)
Tensile strength at break	MPa	D 882, MD D 882, TD	25 17	(66)
Elongation at break	%	D 882, MD D 882, TD	290 500	(66)

*Film and optics properties depend upon processing conditions (see references 9, 10, 60-65). This table presents some representative values of typical high clarity grade LDPE films processed using the following conditions: blow-up ratio = 2:1; die gap = 0.635 mm ; output = 48 kg h^{-1} ; film thickness = $30.5 \mu\text{m}$; die = 203 mm ; frost line height = 330 mm ; melt temperature = 463 K .

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Polypropylene, isotactic

DAVID V. HOWE

ACRONYM PP

CLASS Poly(α -olefins)

STRUCTURE

$$\begin{array}{c} \text{CH}_3 \\ | \\ [-\text{CH}_2\text{CH}-] \end{array}$$

MAJOR APPLICATIONS Fiber, slit tape, cast and biaxially oriented film, containers and closures, automotive interior trim, appliance housings and components, component in elastomeric blends with polyethylene and olefinic rubbers.

PROPERTIES OF SPECIAL INTEREST Low cost; easily processed by injection molding, extrusion, and spinning; can be oriented; excellent resistance to chemicals; low color; can be stabilized to provide good thermal aging stability; moderate strength and stiffness; good toughness when impact modified either in the reactor or by compounding; excellent flexural fatigue resistance; modest clarity.

PREPARATIVE TECHNIQUES Ziegler-Natta polymerization with titanium halide/aluminum alkyl catalyst and, optionally, ether, ester, or silane activator. Catalyst may be deposited on a magnesium chloride support. Slurry and gas phase processes are used. Catalyst systems based on metallocenes are under development. Typical comonomers are ethylene and 1-butene.

Isotacticity

Polymerization Conditions	Isotacticity				Reference
	Isotactic index (% heptane insolubles)	Xylene insolubles	% mmmm	% mm	
MgCl ₂ /TiCl ₄ /DIBP* catalyst modified with TMPIP* and AlEt ₃ prepared at 140°C	—	94	89.3	—	(1)
MgCl ₂ /TiCl ₄ /DIBP* catalyst modified with (i-Bu) ₂ Si(OMe) ₂ and AlEt ₃	97	—	—	—	(2)
MgCl ₂ /TiCl ₄ /DE* catalyst modified with AlEt ₃	95–99	—	—	—	(3)
Various MgCl ₂ or TiCl ₃ supported Ziegler-Natta catalysts	—	—	—	92.2–94.9	(4)

*DIBP = Diisobutyl phthalate; TMPIP = 2,2,6,6-tetramethylpiperidine; DE = 1,3-diether.

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Molecular weight (M_w) and polydispersity index (M_w/M_n)

Polymerization conditions	M_w (g mol ⁻¹)	M_w/M_n	Reference
MgCl ₂ /TiCl ₄ /DIBP catalyst modified with (<i>i</i> -Bu) ₂ Si(OMe) ₂ and AlEt ₃			(2)
H ₂ concentration = 0 mol l ⁻¹	560,000	3.8	
H ₂ concentration = 6.9×10^{-3} mol l ⁻¹	382,000	6.1	
Typical range (extrapolated from melt flow rates of commercial products)	<100,000–>600,000	5–12	(5, 6)
Borealis VC20 82C (MFR: 20 g/10 min)	265,000	4.3	(7)
Typical for controlled rheology (chemically cracked products)	—	<5	(8, 9)
Single site catalyst	—	~2	(10)
Melt flow index			(5)
0.63	646,000	—	
2.9	412,000	—	
11.9	297,000	—	

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Molecular weight of repeat unit	g mol ⁻¹	—CH ₂ —CH(CH ₃)—	42.07	
Morphology (blends, 'impact copolymer')	—	Elastomer content <~60% Elastomer content >~60% (depends upon processing conditions)	Dispersed phase Dispersed or co-continuous phase	(11)
IR (characteristic absorption frequencies)	cm ⁻¹	CH ₃ , CH ₂ , CH stretching CH ₃ antisymmetric bending, CH ₂ bending Various CH ₃ , CH ₂ , and CH bending, wagging, twisting, C—C stretching Various CH ₃ , CH ₂ , and CH bending, wagging, twisting, and rocking, C—C stretching	2956 (s), 2951 (s), 2925 (sh), 2907 (sh), 2880 (s), 2868 (s), 2843 (s) 1459 (sh), 1454 (s) 1377 (s), 1359 (m), 1329 (w), 1305 (w), 1297 (w), 1257 (w), 1219 (w) 1167 (s), 1153 (sh), 997 (s), 973 (s), 841 (s), 809 (m)	(12, 13)
NMR		¹ H NMR ¹³ C NMR		(14–17) (18, 19)
Coefficient of linear thermal expansion	K ⁻¹	ASTM Method D696 From 243 to 273 K From 273 to 303 K From 303 to 330 K	6.5×10^{-5} 1.05×10^{-4} 1.40×10^{-4}	(20)

Polypropylene, isotactic

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Coefficient of thermal expansion (volume, melt)	K ⁻¹	From 448 to 573 K	6.6×10^{-4}	(21)
		From 453 to 503 K	6.7×10^{-4}	(22)
Isothermal compressibility	bar ⁻¹	453 K	1.27×10^{-4}	(22, 23)
		493 K	1.5×10^{-4}	
		533 K	1.78×10^{-4}	
Density	g cm ⁻³	298 K, α -crystalline phase	0.936–0.946	(24, 25, 26)
		298 K, amorphous phase	0.850–0.855	
		298 K, typical commercial material	0.90–0.91	
Solvents		Room temperature	No common solvents	(27)
Solubility parameter	(MPa) ^{1/2}	Inverse phase gas chromatography	18.8	(28)
		Montell Profax 6701	17.3	(29)
Theta temperature	K	$M_w = 28,000$ – $564,000$		(30, 31)
		<i>p</i> -tert-amylphenol	414	
		dibenzyl ether	456	
		biphenyl	398	
Lattice	—	α_1 , α_2 -forms	Monoclinic	(24, 32)
		β -form	Hexagonal	(32)
		γ -form	Orthorhombic	(32, 33, 34)

Form	Space group	Chain conformation	Unit cell dimension (Å)			Unit cell angle (degrees)	Conditions	Reference
			a	b	c			
α_1	C ₁ /c	Helix (3/1)	6.67	20.8	6.50	98.67	Oriented, annealed 413 K	(35)
α_2	P2 ₁ /c	Helix (3/1)	6.65	20.73	6.50	98.67	Oriented, annealed 443 K	(35)
β	P3 ₁ 21	Helix (3/1)	11.03	11.03	6.49	—	—	(32)
γ	Fddd	Helix (3/1)	8.54	9.93	42.41	—	—	(32, 33, 34)

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Heat of fusion	J g ⁻¹	DSC, α -crystalline material (100%)	165	(25)
Degree of crystallinity	%	DSC, density depends upon tacticity and crystallization conditions	50–70	(4, 7, 26)
Glass transition temperature	K	DMA		(7)
		30 Hz	283.7	
		1 Hz	275.5	
Melting point	K	100% crystalline	~459	(36)

Polypropylene, isotactic

Commonly reported mechanical properties*

PROPERTY	UNITS	CONDITIONS	POLYMER TYPE			
			IPP ^(a)	RCP ^(b)	IPC-L ^(c)	ICP-H ^(c)
Yield stress	MPa	ASTM D638	34.5	27.6	26.2	22.0
Yield strain $(L/L_0)_y$	%	ASTM D638	10	14	12	14
Flexural modulus	MPa	ASTM D790	1,389	1,035	1,210	1,000
Izod impact strength ^(d)	J m ⁻¹	ASTM D256	27	55	130	No break
Hardness	Rockwell	ASTM D785	R90	R80	R80	R60
Deflection temperature	K	ASTM D648, 0.45 MPa outer fiber stress	380	360	360	345

* These are typical properties for the classes of materials based on the range of properties reported in references (37) and (38).

^(a)IPP = isotactic propylene homopolymer.

^(b)RCP = ethylene-propylene random copolymer with an ethylene content of about 3%.

^(c)ICP = blends of isotactic propylene homopolymer with ethylene-propylene rubber. These materials are commonly called "impact copolymers," "heterophasic copolymers," or, incorrectly, "block copolymers." These are typically prepared during the polymerization process using a series of reactors. L = low rubber (less than about 15% rubber by weight; typically with an ethylene content of less than about 10%). H = high rubber content blends (greater than about 15% rubber by weight; typically with an ethylene content of at least 7%).

^(d)Impact strength is very dependent upon the molecular weight of the polymer as well as the rubber content of the material. These data are for typical injection molding grade materials.

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Storage modulus	MPa	293 K, Homopolymer, 30 Hz	1,400	(7)
Tan δ	—	293 K, Homopolymer, 30 Hz	0.086	(7)
Poisson ratio	—	296 K	0.38	—
Index of refraction n_D	—	293 K, density 0.9075 g cm ⁻³	1.5030	(39)
Refractive index Increment dn/dc	—	1-Chloronaphthalene and 1,2,4-trichlorobenzene solvents	(see reference)	(40)
Dielectric constant ϵ'	—	At 1 KHz (D150)	2.2-2.3	(26)
		At 1 MHz	2.1-2.3	(41)
Dielectric strength	V cm ⁻¹	298 K (D149)	240,000	(26)
		298 K	217,000-300,000	(41)
		393 K	170,000	(26)
Dissipation factor	—	60 Hz-100 MHz (D510)	0.3-1 ($\times 10^{-3}$)	(26)
		1 MHz	1-3 ($\times 10^{-4}$)	(41)

Polypropylene, isotactic

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Volume resistivity	ohms cm	ASTM D257	10^{16} – 10^{17}	(26, 41)
Surface tension γ	mN m^{-1}	438 K	22.5	(42)
		473 K	21.2	(43)
		495 K	20.2	(42)
Surface free energy	mJ m^{-2}	298 K (calculated from advancing contact angles)	29.0	(43)
Contact angle	degrees	H ₂ O; advancing, 298 K	116	(43)
		CH ₂ I ₂ ; advancing, 298 K	64	
Permeability coefficient	$\frac{\text{m}^3(\text{STP})}{\text{m}^2 \text{ Pa}^{-1}} \text{ m s}^{-1}$	H ₂ O, 298 K	3.83×10^{-16}	(44)
		O ₂ , 298 K (isotropic, all pressures)	7.73×10^{-18}	(45)
		O ₂ , 298 K (12.5:1 draw ratio)	2.12×10^{-18}	(45)
		CO ₂ , 298 K (<1 atm)	2.37×10^{-17}	(46)
		CO ₂ , 298 K (50 atm)	7.50×10^{-17}	(46)
Thermal conductivity	$\text{W m}^{-1} \text{ K}^{-1}$	293 K	0.12	(47)
			0.22	
Melt flow rate	g (10 min)^{-1}	ASTM D1238, 503 K, 2.16 kg	0.2–>500	—
Speed of sound	m s^{-1}	Unoriented		(48)
		298 K	2.5×10^3	
		398 K	125×10^3	(49)
		Oriented		
		Long. dir. 298 K	3.3×10^3	
		Trans. dir. 298 K	2.1×10^3	
Decomposition temperature	K	TGA in helium, Montell Profax 6501	623	(50)
Ignition temperature	K	Calculated from critical heat flux data	736	(51)
Oxygen index	%	ASTM D2863, Montell Profax 6505	17.4	(52)
Scission, G factor	—	γ irradiation		(53, 54)
		Initial	1.2	
		At doses above gel point	0.27	
Cross-linking, G factor	—	γ irradiation	0.07–0.30	(53, 54)
Producers	—	Worldwide in 1994 (see table below for examples)	~117	(55)
Capacity	ktons	Worldwide in 1994 (see table below for examples)	20,492	(55)

Some producers and capacities (from 1996)⁽⁵⁶⁾

Producer	Capacity (ktons)
Montell, Hoofddrop, The Netherlands	3,034
Targor, Mainz, Germany	1,370
Amoco, Chicago, USA	1,183
Japan Polychem, Tokyo, Japan	1,103
Finna, Brussels, Belgium	1,030

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