PA-11 polyamide-11

PARAMETER	UNIT	VALUE	REFERENCES
GENERAL			
Common name	-	polyamide-11, nylon-11; poly(imino-1-oxoundecamethylene)	
IUPAC name	-	poly[imino(1-oxoundecane-1,11-diyl)]	
CAS name	-	poly[imino(1-oxo-1,11-undecanediyl)]	
Acronym	-	PA-11	
CAS number	-	25035-04-5	
HISTORY			
Person to discover	-	Carothers, W H	Carothers, W H, US Patent 2,071,250, DuPont, Feb. 16, 1937.
Date	-	1937	
Details	-	patent for linear condensation polymers including PA11	
SYNTHESIS			
Monomer(s) structure	-	$H_2N(CH_2)_{10}COOH$	
Monomer(s) CAS number(s)	-	2432-99-7	
Monomer(s) molecular weight(s)	dalton, g/mol, amu	201.31	
Monomer ratio	-	100%	
CH_2/CONH ratio		10	
Method of synthesis	-	condensation polymerization reaction	
Temperature of polymerization	°C	240 (star-shaped)	Martino, L; Basilissi, L; Farina, H; Ortenzi, M A; Zini, E; Di Silvestro, G; Scandola, M, Eur. Polym. J., 59, 69-77, 2014.
Time of polymerization	h	4 (star-shaped)	Martino, L; Basilissi, L; Farina, H; Ortenzi, M A; Zini, E; Di Silvestro, G; Scandola, M, Eur. Polym. J., 59, 69-77, 2014.
Number average molecular weight, M_n	dalton, g/mol, amu	16,800-42,355	Robert, E C; Bruessau, R; Dubois, J; Jacques, B; Meijerink, N; Nguye, T Q; Niehaus, D E; Tobisch, W A, Pure Appl. Chem., 76, 11, 2009-25, 2004.
Mass average molecular weight, M_w	dalton, g/mol, amu	28,800-88,800	Robert, E C; Bruessau, R; Dubois, J; Jacques, B; Meijerink, N; Nguye, T Q; Niehaus, D E; Tobisch, W A, Pure Appl. Chem., 76, 11, 2009-25, 2004.
Polydispersity, M_w/M_n	-	1.72-2.5	Robert, E C; Bruessau, R; Dubois, J; Jacques, B; Meijerink, N; Nguye, T Q; Niehaus, D E; Tobisch, W A, Pure Appl. Chem., 76, 11, 2009-25, 2004.
Molar volume at 298K	$cm^3 mol^{-1}$	181.5 (amorphous)	
Van der Waals volume	$cm^3 mol^{-1}$	115.3 (amorphous)	

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PARAMETER	UNIT	VALUE	REFERENCES
STRUCTURE			
Crystallinity	%	16.8-36	Apgar, G, Nylon Plastics Handbook, Kohan, M I, Ed., Hanser, Munich, 1995; Fruebig, P; Kremmer, A; Gerhard-Multhaupt, R; Spanoudaki, A; Pissis, P, J. Chem. Phys., 125, 214701,1-8, 2006; Mancic, L; Osman, R F M; Costa, A M L M; dèAlmeida, J R M; Marinkovic, B A; Rizzo, F C, Mater. Design, 83, 459-67, 2015.
Cell type (lattice)	-	triclinic (α), monoclinic (β), hexagonal (γ, δ, δ')	Apgar, G, Nylon Plastics Handbook, Kohan, M I, Ed., Hanser, Munich, 1995.
Cell dimensions	nm	a:b:c=0.49:0.54:1.49 (α); a:b:c=0.98:1.5:0.80 (β); a:b:c=0.95:2.94:0.45 (γ)	Apgar, G, Nylon Plastics Handbook, Kohan, M I, Ed., Hanser, Munich, 1995; Zhang, Q; Mo, Z; Zhang, H; Liu, S; Cheng, S Z D, Polymer, 42, 5543-47, 2001.
Unit cell angles	degree	α:β:γ=49:77:63 (α); β=65 (β); β=118.5 (γ)	Apgar, G, Nylon Plastics Handbook, Kohan, M I, Ed., Hanser, Munich, 1995; Zhang, Q; Mo, Z; Zhang, H; Liu, S; Cheng, S Z D, Polymer, 42, 5543-47, 2001.
Crystallite size	nm	20.4	Rajesh, J J; Bijwe, J, Wear, 661-68, 2005.
Spacing between crystallites	nm	0.37-0.44 (intersheet distance)	
Polymorphs	-	α (triclinic), β (monoclinic), γ, δ, δ' (hexagonal)	Zhang, Q; Mo, Z; Zhang, H; Liu, S; Cheng, S Z D, Polymer, 42, 5543-47, 2001.
COMMERCIAL POLYMERS			
Some manufacturers	-	Arkema	
Trade names	-	Rilsan B	
PHYSICAL PROPERTIES			
Density at 20^{o}C	g cm^{-3}	1.026-1.06; 1.15 (crystalline); 1.01 (amorphous)	Apgar, G, Nylon Plastics Handbook, Kohan, M I, Ed., Hanser, Munich, 1995.
Melting temperature, DSC	^{o}C	176-198	
Decomposition temperature	^{o}C	240-270	Oliveira, M J; Botelho, G, Polym. Deg. Stab., 93, 139-46, 2008.
Onset degradation temperature	^{o}C	390.7 (nitrogen), 395.2 (air)	Filippone, G; Carroccio, S C; Curcuruto, G; Passaglia, E; Cambarotti, C; Dintcheva, N T, Polymer, 73, 102-10, 2015.
Thermal expansion coefficient, 23-80^{o}C	^{o}C^{-1}	8.5E-5	
Thermal conductivity, melt	W m^{-1} K^{-1}	0.267-0.29	Boudenne, A; Ibos, L; Gehin, E; Candau, Y, J. Phys. D: Appl. Phys., 37, 132-39, 2004.
Glass transition temperature	^{o}C	35-46	
Specific heat capacity	J K^{-1} kg^{-1}	1753	
Hansen solubility parameters, δ_D, δ_P, δ_H	MPa$^{0.5}$	17.0, 4.4, 10.6	
Interaction radius		5.1	
Hildebrand solubility parameter	MPa$^{0.5}$	calc.=19.2	
Dielectric constant at 100 Hz/1 MHz	-	3.9/3.1	

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PARAMETER	UNIT	VALUE	REFERENCES
Volume resistivity	ohm-m	1E12	
Coefficient of friction	-	0.1-0.3	
Contact angle of water, 20°C	degree	82	
MECHANICAL & RHEOLOGICAL PROPERTIES			
Tensile strength	MPa	37-69	
Tensile modulus	MPa	1,300	
Tensile stress at yield	MPa	31-41	
Elongation	%	310	
Tensile yield strain	%	18-24	
Flexural modulus	MPa	290-1,150	
Young's modulus	MPa	344; 365 (theoretical)	Peeters, A; van Alsenoy, C; Bartha, F; Bogar, F; Zhang, M-L; van Doren, V E, Int. J. Quantum Chem. 87, 303-10, 2002.
Charpy impact strength, notched, 23°C	kJ m^{-2}	5-15	
Charpy impact strength, notched, -30°C	kJ m^{-2}	5-13	
Izod impact strength, unnotched, 23°C	J m^{-1}	116	
Crack growth velocity	x 10^{-6} m s^{-1}	344	Rajesh, J J; Bijwe, J, Tribology lett., 18, 3, 331-40, 2005.
Fracture energy	x 10^4 J m^{-2}	5.89	Rajesh, J J; Bijwe, J, Tribology lett., 18, 3, 331-40, 2005.
Ductility factor	mm	17.60	Rajesh, J J; Bijwe, J, Tribology lett., 18, 3, 331-40, 2005.
Stress necessary to cause spontaneous fracture	MPa	66.7	Rajesh, J J; Bijwe, J, Tribology lett., 18, 3, 331-40, 2005.
Shear strength	MPa	35-42	
Tenacity (fiber) (standard atmosphere)	cN tex^{-1} (daN mm^{-2})	45-68 (47-70)	Fourne, F, Synthetic Fibers. Machines and Equipment Manufacture, Properties. Carl Hanser Verlag, 1999.
Tenacity (wet fiber, as % of dry strength)	%	100	Fourne, F, Synthetic Fibers. Machines and Equipment Manufacture, Properties. Carl Hanser Verlag, 1999.
Fineness of fiber (titer)	dtex	3-7	Fourne, F, Synthetic Fibers. Machines and Equipment Manufacture, Properties. Carl Hanser Verlag, 1999.
Length (elemental fiber)	mm	continuous filament	Fourne, F, Synthetic Fibers. Machines and Equipment Manufacture, Properties. Carl Hanser Verlag, 1999.
Shore D hardness	-	64-75	
Rockwell hardness	-	R106	
Viscosity number	ml g^{-1}	151	
Melt viscosity, shear rate=0 s^{-1}	Pa s	2,260	
Moisture absorption, equilibrium 23°C/50% RH	%	0.9-1.1	

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PARAMETER	UNIT	VALUE	REFERENCES
CHEMICAL RESISTANCE			
Acid dilute/concentrated	-	good-poor	
Alcohols	-	fair-poor	
Alkalis	-	good	
Aliphatic hydrocarbons	-	good	
Aromatic hydrocarbons	-	good	
Esters	-	good	
Greases & oils	-	good	
Halogenated hydrocarbons	-	good-poor	
Ketones	-	good	
Good solvent	-	higher primary alcohols, DMF, DMSO, hexafluoropropanol, formic acid/dichloromethane	
FLAMMABILITY			
Ignition temperature	°C	400	
Autoignition temperature	°C	440	
Limiting oxygen index	% O_2	20-27	
Volatile products of combustion	-	CO_2, CO, unsaturated hydrocarbons, methane	Levchik, S V; Costa, L; Camino, G, Polym. Deg. Stab., 36, 31-41, 1992.
WEATHER STABILITY			
Spectral sensitivity	nm	385 (increases on heating)	Oliveira, M J; Botelho, G, Polym. Deg. Stab., 93, 139-46, 2008.
BIODEGRADATION			
Stabilizers	-	silver	
PROCESSING			
Typical processing methods	-	electrospinning, extrusion, injection molding, rotational molding, spinning	
Processing temperature	°C	209-222 (extrusion); 218-235 (injection molding)	
Applications	-	aeronautics, automotive, bearings, break lines, bushings, flexible pipe, food contact, fuel tanks, insulators, marine, medical, natural gas, oil, skis, ski boots, tennis rackets, transport, wire & cable	
Outstanding properties	-	low moisture absorption, monomer is made by thermal cracking of ricinoleic acid from renewable source (castor oil)	
BLENDS			
Suitable polymers	-	PA6,6, PA6,10, PANI, PE, polyepichlorohydrin, PSU, PVDF, starch	
Compatibilizers	-	EPDM-MAH	
ANALYSIS			
FTIR (wavenumber-assignment)	cm^{-1}/-	amide – 1640, 1543; C-C – 1126	Yu, H H, Mater. Chem. Phys., 56, 289-93, 1998.
Raman (wavenumber-assignment)	cm^{-1}/-	amide 1 – 1640; C-C – 1063/1107	Hendra, P J; Maddams, W F; Royaud, I A M; Willis, H A; Zichy, V, Spectrochim. Acta, 64A, 5, 747-56, 1990.

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PARAMETER	UNIT	VALUE	REFERENCES
NMR (chemical shifts)	ppm	see ref.	Davis, R D; Jarrett, W L; Mathias, L J, Polymer, 42, 2621-26, 2001.