PA-6,6 polyamide-6,6

PARAMETER	UNIT	VALUE	REFERENCES
GENERAL			
Common name	-	polyamide-6,6, nylon-6,6, poly(iminoadipoyliminohexamethylene), poly(hexamethylene adipamide)	
IUPAC name	-	poly[N,N'-(hexane-1,6-diyl)adipamide]	
CAS name	-	poly[imino(1,6-dioxo-1,6-hexanediyl)imino-1,6-hexanediyl]	
Acronym	-	PA-6,6	
CAS number	-	32131-17-2	
RTECS number	-	DG0875000	
HISTORY			
Person to discover	-	Wallace Hume Carothers	
Date	-	February 28, 1935	
Details	-	deliberate research in DuPont resulted in synthesis of small amount of viscous mass which was capable of forming fibers	
SYNTHESIS			
Monomer(s) structure	-	$H_2N(CH_2)_6NH_2$ $HO\overset{O}{\overset{\|}{C}}(CH_2)_4\overset{O}{\overset{\|}{C}}OH$	
Monomer(s) CAS number(s)	-	124-09-4; 124-04-9	
Monomer(s) molecular weight(s)	dalton, g/mol, amu	116.21; 146.14	
Monomer ratio	-	0.79; 0.79:1	
CH_2/CONH ratio		5	
Number average molecular weight, M_n	dalton, g/mol, amu	17,500-18,040	
Mass average molecular weight, M_w	dalton, g/mol, amu	16,000-30,000	
Polydispersity, M_w/M_n	-	1.7-2.1	
Molar volume at 298K	cm^3 mol^{-1}	calc.=183 (crystalline); 211.5 (amorphous); exp.=193-208	
Van der Waals volume	cm^3 mol^{-1}	calc.=128.3 (crystalline); 128.3 (amorphous)	
Chain-end groups	-	NH_2 – 0.6; COOH – 0.8	Davis, R D; Jarrett, W L; Mathias, L J, Polymer, 42, 2621-26, 2001.
STRUCTURE			
Crystallinity	%	32-65 (DMA, X-ray); 43 (dry); 39 (wet)	Extrand, C W, J. Colloid Interface Sci., 248, 136-42, 2002.
Cell type (lattice)	-	monoclinic, triclinic (α); pseudohexagonal (γ)	
Cell dimensions	nm	a:b:c=0.914:0.484:1.668 (monoclinic); 0.49:0.54:1.72 (triclinic)	Jones, N A; Atkins, E D T; Hill, M J; Cooper, S J; Franco, L, Polymer, 38, 11, 2689-99, 1997.
Unit cell angles	degree	β: 67 (monoclinic); $\alpha:\beta:\gamma$=48.5:77:63.5 (triclinic)	Jones, N A; Atkins, E D T; Hill, M J; Cooper, S J; Franco, L, Polymer, 38, 11, 2689-99, 1997.
Number of chains per unit cell	-	1 or 2	
Crystallite size	nm	15.6	Rajesh, J J; Bijwe, J, Wear, 661-68, 2005.

PARAMETER	UNIT	VALUE	REFERENCES
Spacing between crystallites	nm	0.37-0.65	Extrand, C W, J. Colloid Interface Sci., 248, 136-42, 2002; Elzein, T; Brogly, M; Castelein, G; Schultz, J, J. Polym. Sci. B, 40, 1464-76, 2002; Sengupta, R; Tikku, V K; Somani, A K; Chaki, T K; Bhowmick, A K, Radiat. Phys. Chem., 72, 625-33, 2005.
Polymorphs	-	α, γ	
Cis content	%	1.1	Davis, R D; Jarrett, W L; Mathias, L J, Polymer, 42, 2621-26, 2001.
Lamellae thickness	nm	17	Elzein, T; Brogly, M; Castelein, G; Schultz, J, J. Polym. Sci. B, 40, 1464-76, 2002.
Rapid crystallization temperature	°C	230	Adriaensens, P; Pollaris, A; Carlleer, R; Vanderzande, D; Gelan, J; Litvinov, V M; Tijssen, J, Polymer, 42, 7943-52, 2001.
COMMERCIAL POLYMERS			
Some manufacturers	-	BASF; DSM; DuPont; EMS	
Trade names	-	Ultramid A; Akulon; Zytel; Grilon	
PHYSICAL PROPERTIES			
Density at 20°C	g cm^{-3}	1.05-1.14; 0.969 (melt); 1.213-1.500 (13-43% glass fiber, dry)	
Bulk density at 20°C	g cm^{-3}	0.5-0.8	
Color	-	white	
Refractive index, 20°C	-	1.565-1.568	
Birefringence	-	1.582/1.519-1.53	
Odor		odorless	
Melting temperature, DSC	°C	257-270; 262 (13-43% glass fiber, dry)	
Decomposition temperature	°C	340	
Activation energy of thermal degradation	kJ mol^{-1}	91	
Thermal expansion coefficient, -40 to 160°C	10^{-4} °C^{-1}	1; 0.09-1.58 (13-43% glass fiber, dry)	
Thermal conductivity, melt	W m^{-1} K^{-1}	0.23-0.343	Benaarbia, A; Chrysochoos, A; Robert, G, Polym. Testing, 34, 155-67, 2014.
Glass transition temperature	°C	56-70 (dry); 35 (50% RH); -15 (100% RH)	
Specific heat capacity	J K^{-1} kg^{-1}	1638-1,700; 2,750 (melt)	
Heat of fusion	kJ kg^{-1}	192-196	
Temperature index (50% tensile strength loss after 20,000 h/5000 h)	°C	65-85; 125-130 (13-43% glass fiber, dry)	Padey, D; Walling, J; Wood A, Polymers in Defence and Aerospace 2007, Rapra, 2007, paper 15.
Heat deflection temperature at 0.45 MPa	°C	200-230; 258-264 (13-43% glass fiber, dry)	
Heat deflection temperature at 1.8 MPa	°C	70-86; 238-256 (13-43% glass fiber, dry)	
Vicat temperature VST/A/50	°C	255 (13-43% glass fiber, dry)	
Enthalpy of melting	J g^{-1}	83	Cerrutti, P; Carfagna, C, Polym. Deg. Stab., 95, 2405-12, 2010.
Hansen solubility parameters, δ_D, δ_P, δ_H	MPa$^{0.5}$	17.2, 9.9, 16.5; 18.6, 5.1, 12.3	

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PARAMETER	UNIT	VALUE	REFERENCES
Interaction radius		4.4; -;	
Hildebrand solubility parameter	$MPa^{0.5}$	exp.=22.87-25.8	
Surface tension	mN m^{-1}	calc.=46.5; exp.=36-44	
Dielectric constant at 100 Hz/1 MHz	-	4.0/3.6	
Relative permittivity at 100 Hz	-	3.2-4.3 (dry); 10.3-15 (conditioned); 3.9-4.5 (13-43% glass fiber, dry)	
Relative permittivity at 1 MHz	-	3-3.6 (dry); 4.2-4.3 (conditioned); 3.2-4.1 (13-43% glass fiber, dry)	
Dissipation factor at 100 Hz	E-4	60-150 (dry); 2,000-2,400 (conditioned); 100 (13-43% glass fiber, dry)	
Dissipation factor at 1 MHz	E-4	170-240 (dry); 750-1,200 (conditioned); 145 (13-43% glass fiber, dry)	
Volume resistivity	ohm-m	1E13 (dry); 3E9-1E11 (saturated at 50% RH, 20°C); 6E9 (saturated at 100% RH, 20°C); 1E14 (13-43% glass fiber, dry); 1E10 (13-43% glass fiber, conditioned)	
Surface resistivity	ohm	1E14 (conditioned); 1E12 (13-43% glass fiber, dry)	
Electric strength K20/P50, d=0.60.8 mm	kV mm^{-1}	30-30.5; 25 (conditioned); 25-27 (13-43% glass fiber, dry)	
Comparative tracking index, CTI, test liquid A	-	>600; >600 (13-43% glass fiber, dry)	
Comparative tracking index, CTIM, test liquid B	-	>600 (13-43% glass fiber, dry)	
Arc resistance	MV/m	145 (13-43% glass fiber, dry)	
Power factor	-	0.04	
Percolation threshold for MWCNT	wt%	0.040.05	Krause, B; Boldt, R; Haussler, L; Poetschke, P, Compos. Sci. Tecnol., 114, 119-25, 2015.
Coefficient of friction	-	0.35-0.5	
Diffusion coefficient of nitrogen	cm^2 s^{-1} x10^6	0.0002	
Diffusion coefficient of water vapor	cm^2 s^{-1} x10^6	0.002 (20°C); 0.035 (60°C); 0.35 (100°C)	
Contact angle of water, 20°C	degree	67.6-72; 68.5/40.9 (ascending/receding)	
Surface free energy	mJ m^{-2}	44.3	
Speed of sound	m s^{-1}	43.3-46.1	
Acoustic impedance		2.90-3.15	
Attenuation	dB cm^{-1}, 5 MHz	2.9-16.0	
MECHANICAL & RHEOLOGICAL PROPERTIES			
Tensile strength	MPa	70-88 (dry); 120-235 (13-43% glass fiber, dry); 75-167 (13-43% glass fiber, conditioned)	
Tensile modulus	MPa	3,000-3,600 (dry); 1,200-1,800 (conditioned); 5,500-14,000 (13-43% glass fiber, dry); 3,500-11,000 (13-43% glass fiber, conditioned)	
Tensile stress at yield	MPa	82-95; 55-60 (conditioned)	
Tensile creep modulus, 1000 h, elongation 0.5 max	MPa	7,960 (13-43% glass fiber, conditioned)	
Elongation	%	10-45 (dry); >50 to >100 (conditioned); 3 (13-43% glass fiber, dry); 4-13 (13-43% glass fiber, conditioned)	
Tensile yield strain	%	4-5 (dry); 20-27 (conditioned)	

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PARAMETER	UNIT	VALUE	REFERENCES
Flexural strength	MPa	125; 160-340 (13-43% glass fiber, dry); 100-260 (13-43% glass fiber, conditioned); 226-263 (50% glass fiber)	Teixeira, D; Giovanela, M; Gonella, LB; Crespo, J S, Mater Design, 85, 695-706, 2015.
Flexural modulus	MPa	2,800 (dry); 1,070-1,200 (conditioned); 4,800-12,000 (13-43% glass fiber, dry); 2,900-8,900 (13-43% glass fiber, conditioned)	
Young's modulus	GPa	2.8	Sasayama, T; Okabe, T; Aoyagi, Y; Nishikawa, M, Composites: Part A, 52, 45-54, 2013.
Charpy impact strength, unnotched, 23°C	kJ m^{-2}	no break; 40-100 (13-43% glass fiber, dry); 70-105 (13-43% glass fiber, conditioned)	
Charpy impact strength, unnotched, -30°C	kJ m^{-2}	no break to 400; 40-85 (13-43% glass fiber, dry); 45-105 (13-43% glass fiber, conditioned)	
Charpy impact strength, notched, 23°C	kJ m^{-2}	4.9-6 (dry); 12-20 (conditioned); 4-16 (13-43% glass fiber, dry); 5-19 (13-43% glass fiber, conditioned)	
Charpy impact strength, notched, -30°C	kJ m^{-2}	3.8-6 (dry); 3-6 (conditioned); 4.0-12 (13-43% glass fiber, dry); 6-12 (13-43% glass fiber, conditioned)	
Crack growth velocity	x 10^{-6} m s^{-1}	508	Rajesh, J J; Bijwe, J, Tribology lett., 18, 3, 331-40, 2005.
Fracture energy	x 10^{4} J m^{-2}	6.52	Rajesh, J J; Bijwe, J, Tribology lett., 18, 3, 331-40, 2005.
Ductility factor	mm	15.14	Rajesh, J J; Bijwe, J, Tribology lett., 18, 3, 331-40, 2005.
Stress necessary to cause spontaneous fracture	MPa	129.16	Rajesh, J J; Bijwe, J, Tribology lett., 18, 3, 331-40, 2005.
Poisson's ratio	-	0.3-0.5	
Rockwell hardness	-	M105 (13-43% glass fiber, dry); M90 (13-43% glass fiber, conditioned); 125R (13-43% glass fiber, dry); 118 (13-43% glass fiber, conditioned)	
Ball indention hardness at 358 N/30 S (ISO 2039-1)	MPa	295 (13-43% glass fiber, dry); 218 (13-43% glass fiber, conditioned)	
Shrinkage	%	0.95-1.6; 0.2-1.7 (13-43% glass fiber, dry)	
Brittleness temperature (ASTM D746)	°C	-80 to -100 (dry); -65 to -85 (50% RH)	
Water absorption, equilibrium in water at 23°C	%	8.5-9.0; 4.7-7.6 (13-43% glass fiber, dry)	
Moisture absorption, equilibrium 23°C/50% RH	%	2.3-3.4; 1.4-2.2 (13-43% glass fiber, dry)	
CHEMICAL RESISTANCE			
Acid dilute/concentrated	-	good/poor	
Alcohols	-	good	
Alkalis	-	good/poor	
Aliphatic hydrocarbons	-	good	
Aromatic hydrocarbons	-	fair	
Esters	-	good	
Greases & oils	-	good	
Halogenated hydrocarbons	-	poor	
Ketones	-	good	
Θ solvent, Θ-temp.=20°C	-	carbon tetrachloride/m-cresol/cyclohexane	
Good solvent	-	acetic acid, benzyl alcohol, chloroacetic acid, DMSO, formamide, formic acid, HCl, HF, H_3PO_3, H_2SO_4, methanol, phenol, sulfur dioxide, trichloroethanol, trifluoroethanol	

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PARAMETER	UNIT	VALUE	REFERENCES
Non-solvent	-	aliphatic alcohols, aliphatic esters, aliphatic ketones, chloroform, diethyl ether, hydrocarbons	
Effect of EtOH sterilization (tensile strength retention)	%	95-105	Navarrete, L; Hermanson, N, Antec, 2807-18, 1996.
FLAMMABILITY			
Ignition temperature	°C	420	
Autoignition temperature	°C	530	
Limiting oxygen index	% O_2	28-31; 21.5-24 (13-43% glass fiber, dry)	
Heat release	kW m^{-2}	328	Braun, U; Scchartel, B; Fichera, M A; Jaeger, C, Polym. Deg. Stab., 92, 1528-45, 2007.
Heat of combustion	J g^{-1}	30,900	Walters, R N; Hacket, S M; Lyon, R E, Fire Mater., 24, 5, 245-52, 2000.
Volatile products of combustion	-	H_2O, CO_2, cyclopentanone, hexylamine, hexamethylene diamine	
UL rating	-	HB to V-2; HB (13-43% glass fiber)	
WEATHER STABILITY			
Excitation wavelengths	nm	295, 310, 315	
Emission wavelengths	nm	423, 450, 460, 465	
Important initiators and accelerators	-	chlorinated water, conjugated carboxylic unsaturations, products of photooxidation, titanium dioxide, zinc oxide, derivatives of anthraquinone, oxyethylsulfonic red and yellow, monochlorotriazine red and yellow, copper compounds	
Products of degradation	-	amines, carbon monoxide, hydrogen, hydrocarbons, crosslinks (photolysis); amines, carbon monoxide, carbon dioxide, acids, aldehydes, ketones, water, ammonia, hydroperoxides, pyrrole, ethylene (photooxidation)	
BIODEGRADATION			
Typical biodegradants	-	cutinase from *Fusarium solani pisi*	Araujo, R; Silva, C; O'Neill, A; Micaelo, N; Guebitz, G; Soares, C M; Casal, M; Cavaco-Paulo, A, J. Biotechnol., 128, 849-57, 2007.
TOXICITY			
HMIS: Health, Flammability, Reactivity rating	-	1/1/0	
Carcinogenic effect	-	not listed by ACGIH, IARC, or NTP	
Oral rat, LD_{50}	mg kg^{-1}	>10,000	
Skin rabbit, LD_{50}	mg kg^{-1}	not a skin irritant	
PROCESSING			
Typical processing methods	-	injection molding	
Preprocess drying: temperature/time/residual moisture	°C/h/%	60-80/2-4/0.04-0.2	
Processing temperature	°C	280-305 (injection molding)	
Processing pressure	MPa	35-125 (injection pressure); 0-0.35 (back pressure)	
Applications	-	aerospace, automotive (fuel systems, under-the-hood applications such as shrouds and ducts), composite structures, stock shapes, waste water treatment	

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PARAMETER	UNIT	VALUE	REFERENCES
Outstanding properties	-	mechanical strength, drawing behavior	
BLENDS			
Suitable polymers	-	LCP, PA6, PBT, PP, SEBS	
ANALYSIS			
FTIR (wavenumber-assignment)	cm^{-1}/-	amides – 1635; conjugated carbonyls – 1700; aldehydes – 1725; isolated carboxylix acids – 1760	Yoshioka, Y; Tashiro, K; Ramesh, C, J. Polym. Sci. B, 41, 1294-1307, 2003; Cerruti, P; Lavorgna, M; Carfagna, C; Nicolais, L, Polymer, 46, 4571-83, 2005.
NMR (chemical shifts)	ppm	see ref.	Davis, R D; Jarrett, W L; Mathias, L J, Polymer, 42, 2621-26, 2001.
x-ray diffraction peaks	degree	13.5, 20.2, 22.3, 23.8	Sengupta, R; Tikku, V K; Somani, A K; Chaki, T K; Bhowmick, A K, Radiat. Phys. Chem., 72, 625-33, 2005.