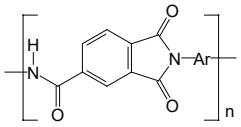
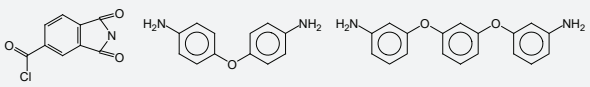
PAI poly(amide imide)

PARAMETER	UNIT	VALUE	REFERENCES
GENERAL			
Common name	-	poly(amide imide)	
ACS name	-	5-isobenzofurancarboxylic acid, 1,3-dihydro-1,3-dioxo-, polymer with 1,3-benzenediamine and 4,4'-oxybis[benzenamine] (Torlon)	
Acronym	-	PAI	
CAS number	-	42955-03-3; 914797-27-6	
Formula (Torlon)			
The most relevant sources of additional data			Torlon, Polyamide-imide, Design guide, Solvay Advanced Polymers, 2003, T-50246
HISTORY			
Person to discover	-	George, N J	George, N J, US Patent 3,554,984, Jan. 12, 1971.
Date	-	1971 (filed 1965)	
Details	-	PAI resin obtained from trimellitic anhydride and diamines	
SYNTHESIS			
Monomer(s) structure	-		Robertson, G P; Guiver, M D; Yoshikawa, M; Brownstein, S, Polymer, 45, 1111-17, 2004.
Monomer(s) CAS number(s)	-	1204-28-0; 101-80-4; 2479-46-1	
Monomer(s) molecular weight(s)	dalton, g/mol, amu	210.57; 200.24; 292.34	
Monomer ratio	-	1:0.7:0.3	Robertson, G P; Guiver, M D; Yoshikawa, M; Brownstein, S, Polymer, 45, 1111-17, 2004.
Formulation example	-	the above set of monomers is used in the production of Torlon 4000	Robertson, G P; Guiver, M D; Yoshikawa, M; Brownstein, S, Polymer, 45, 1111-17, 2004
Method of synthesis	-	polymer can be obtained by reacting the trimellitic anhydride chloride with m-phenylenediamine and 4,4'-oxydianiline, followed by dehydratation; other methods include isocyanate route and direct polymerization	Robertson, G P; Guiver, M D; Yoshikawa, M; Brownstein, S, Polymer, 45, 1111-17, 2004; Fink, J K, High Performance Polymers, William Andrew, 2008.
Yield	%	>95	Liaw, D-J; Chen, W-H, Polym. Deg. Stab., 91, 8, 1731-39, 2006.
Number average molecular weight, M_n	dalton, g/mol, amu	18,400-86,000	
Mass average molecular weight, M_w	dalton, g/mol, amu	20,100-220,000	
Polydispersity, M_w/M_n	-	1.74-2.56	Liaw, D-J; Chen, W-H, Polym. Deg. Stab., 91, 8, 1731-39, 2006.
Molecular cross-sectional area, calculated	$cm^2 \times 10^{-16}$	18.6	
Radius of gyration	nm	1.49-3.02	Chen, Y; Liu, Q L; Zhu, A M; Zhang, Q G; Wu, J W, J. Membrane Sci., 348, 204-12, 2010.

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PARAMETER	UNIT	VALUE	REFERENCES
COMMERCIAL POLYMERS			
Some manufacturers	-	Solvay	
Trade names	-	Torlon	
PHYSICAL PROPERTIES			
Density at 20°C	g cm^{-3}	1.38-1.42; 1.61 (30% glass fiber); 1.48-1.49 (30% carbon fiber); 1.47 (graphite)	
pH	-	4.5	Wolff, M F H; Antonyuk, S; Heinrich, S; Schneider, G A, Particuology, 17, 92-96, 2014
Refractive index, 20°C	-	1.656	Bryce, R M; Nguyen, H T; Clement, T; Haugen, C J; Tykwinski, R R; DeCorby, R G; McMullin, J N, Thin Solid Films, 458, 233-36, 2004.
Melting temperature, DSC	°C	357	
Thermal expansion coefficient, 23-80°C	$°C^{-1}$	1.7-3.1E-5; 0.16E-4 (30% glass fiber); 5E-4 (30% carbon fiber); 1.4E-5 (graphite)	
Thermal conductivity, melt	W m^{-1} K^{-1}	0.259; 0.36 (30% glass fiber); 0.518 (30% carbon fiber); 0.533 (graphite)	
Glass transition temperature	°C	206-326	Liaw, D-J; Hsu, P-N; Chen, W-H; Lin, S-L, Macromolecules, 35, 12, 4669-76, 2002; Chen, Y; Liu, Q L; Zhu, A M; Zhang, Q G; Wu, J W, J. Membrane Sci., 348, 204-12, 2010.
Specific heat capacity	J K^{-1} kg^{-1}	1013; 959 (30% glass fiber); 963 (30% carbon fiber); 1005 (graphite)	
Maximum service temperature	°C	400	
Long term service temperature	°C	-150 to 260	
Temperature index (50% tensile strength loss after 20,000 h/5000 h)	°C	200	Padey, D; Walling, J; Wood A, Polymers in Defence and Aerospace 2007, Rapra, 2007, paper 15.
Heat deflection temperature at 1.8 MPa	°C	278; 282 (30% glass fiber); 282 (30% carbon fiber); 279 (graphite)	
Zeta potential	mV	30	Wolff, M F H; Antonyuk, S; Heinrich, S; Schneider, G A, Particuology, 17, 92-96, 2014
Dielectric constant at 100 Hz/1 MHz	-	4.2/3.9; 4.4/4.2 (30% glass fiber); 6.0/5.4 (graphite)	
Dissipation factor at 1000 Hz		0.026; 0.022 (30% glass fiber); 0.037 (graphite)	
Dissipation factor at 1 MHz		0.031; 0.05 (30% glass fiber); 0.042 (graphite)	
Volume resistivity	ohm-m	2E15, (30% glass fiber); 8E13 (graphite)	
Surface resistivity	ohm	5E18; 1E18 (30% glass fiber); 8E17 (graphite)	
Electric strength K20/P50, d=0.60.8 mm	kV mm^{-1}	23; 33 (30% glass fiber)	
MECHANICAL & RHEOLOGICAL PROPERTIES			
Tensile strength	MPa	147-192; 205-221 (30% glass fiber); 203 (30% carbon fiber); 163 (graphite)	
Tensile modulus	MPa	4,480-4,900; 9,360-14,500 (30% glass fiber); 22,220 (30% carbon fiber); 6,555 (graphite)	
Elongation	%	15-35; 2.3-7 (30% glass fiber)	
Flexural strength	MPa	196-241; 333 (30% glass fiber); 350 (30% carbon fiber); 215 (graphite)	

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Flexural modulus	MPa	3620-5030; 11,730 (30% glass fiber); 16,560 (30% carbon fiber); 6,900 (graphite)	
Compressive strength	MPa	117-221; 264 (30% glass fiber); 255 (30% carbon fiber); 166 (graphite)	
Izod impact strength, unnotched, 23°C	J m^{-1}	1068-1100; 507-530 (30% glass fiber); 320-342 (30% carbon fiber); 406 (graphite)	
Izod impact strength, notched, 23°C	J m^{-1}	138-144; 80 (30% glass fiber); 48 (30% carbon fiber); 64 (graphite)	
Poisson's ratio	-	0.45; 0.43 (30% glass fiber); 0.39 (30% carbon fiber); 0.39 (graphite)	
Rockwell hardness	E	86-127; 94 (30% glass fiber); 72 (graphite)	
Shrinkage	%	0.6-0.85; 0.1-0.25 (30% glass fiber); 0.0-0.15 (30% carbon fiber)	
Intrinsic viscosity, 25°C	dl g^{-1}	0.83-1.51	Liaw, D-J; Chen, W-H, Polym. Deg. Stab., 91, 8, 1731-39, 2006.
Water absorption, equilibrium in water at 23°C	%	0.33; 0.24 (30% glass fiber); 0.26 (30% carbon fiber); 0.28 (graphite)	
Moisture absorption, equilibrium 23°C/50% RH	%	1.6-2.5	
CHEMICAL RESISTANCE			
Acid dilute/concentrated	-	excellent to poor	
Alcohols	-	excellent to poor	
Alkalis	-	poor	
Aliphatic hydrocarbons	-	excellent	
Aromatic hydrocarbons	-	excellent	
Esters	-	excellent	
Greases & oils	-	excellent	
Halogenated hydrocarbons	-	excellent	
Ketones	-	excellent	
Non-solvent	-	hot NH_4OH	
FLAMMABILITY			
Ignition temperature	°C	570	
Autoignition temperature	°C	620	
Limiting oxygen index	% O_2	39.5-45; 51 (30% glass fiber); 52 (30% carbon fiber); 44 (graphite)	Abdolmaleki, A; Mallakpour, S; Rostami, M, Prog. Org. Coat., 80, 71-6, 2015.
NBS smoke chamber, minimum light transmittance	%, smol-dering/ flaming	92/6; 96/56 (30% glass fiber); 95/28 (30% carbon fiber)	
Char at 500°C	%	53.6-54.9	Lyon, R E; Walters, R N, J. Anal. Appl. Pyrolysis, 71, 27-46, 2004.
Heat of combustion	J g^{-1}	24,970	Walters, R N; Hacket, S M; Lyon, R E, Fire Mater., 24, 5, 245-52, 2000.
Volatile products of combustion	-	CO_2, CO	
UL 94 rating	-	94 V-0	

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PARAMETER	UNIT	VALUE	REFERENCES
WEATHER STABILITY			
UV absorption maximum	nm	296-324	Behniafar, H; Beit-Saeed, A; Hadian, A, Polym. Deg. Stab., 94, 1991-98, 2009.
Weather-O-Meter exposure	10,000 h in carbon arc	tensile strength - 93% retention, elongation - 100% retention	
TOXICITY			
NFPA: Health, Flammability, Reactivity rating	-	0-1/1/0	
Carcinogenic effect	-	not listed by ACGIH, NIOSH, NTP	
PROCESSING			
Typical processing methods	-	coating, compression molding, extrusion, injection molding, lamination, machining	
Preprocess drying: temperature/ time/residual moisture	^{o}C/h/%	177/3/0.05	
Processing temperature	^{o}C	304-371 (injection molding)	
Processing pressure	MPa	6.89 (back pressure)	
Additives used in final products	-	Fillers: carbon fiber, glass fiber, graphene, graphite, molybdenium dioxide, MWCNT, PTFE powder (0.5%), silica, talc, TiO_2 (3%), zinc oxide	
Applications	-	automotive and aircraft parts, bonding tapes, bushings, business equipment, chip-on-film, compressor valve plates, electrical, electronic bearings, fasteners, gears, hollow fiber membranes, magnet wire coating, membranes, metal compressors in aerospace applications, piston rings and seals, plastic engine, pump housings, space shuttle, thermal transfer sheet for printers, wear pads	
Outstanding properties	-	performance temperature, high strength, wear resistance, thermal stability, low expansion coefficient, and resistance to automotive and aviation fluids	
BLENDS			
Suitable polymers	-	PAEK, PI, PVAI, PVP	
ANALYSIS			
FTIR (wavenumber-assignment)	cm^{-1}/-	imide – 1778; C=O – 1717; imide ring – 1109, 725	Setiawan, L; Wang, R; Li, K; Fane, A G, J. Membrane Sci., 369, 196-205, 2011.
NMR (chemical shifts)	ppm	benzene ring – 8.11-8.25 and 8.50-8.70	Robertson, G P; Guiver, M D; Yoshikawa, M; Brownstein, S, Polymer, 45, 1111-17, 2004.