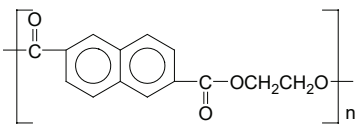
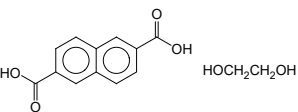


PEN poly(ethylene 2,6-naphthalate)

PARAMETER	UNIT	VALUE	REFERENCES
GENERAL			
Common name	-	poly(ethylene 2,6-naphthalate)	
CAS name	-	poly(oxy-1,2-ethanediylloxycarbonyl-2,6-naphthalenediyl-carbonyl) (24968-11-4); 2,6-naphthalenedicarboxylic acid, polymer with 1,2-ethanediol (25230-87-9)	
Acronym	-	PEN	
CAS number	-	24968-11-4; 25230-87-9	
Formula			
HISTORY			
Person to discover	-	Cook, J G; Huggill, H P W; Lowe, A R	
Date	-	1948	
Details	-	ICI obtained first patent in 1948	
SYNTHESIS			
Monomer(s) structure	-		
Monomer(s) CAS number(s)	-	1141-38-4; 107-21-1	
Monomer(s) molecular weight(s)	dalton, g/mol, amu	216.193; 62.07	
Monomer(s) expected purity(ies)	%	99.6	
Monomer ratio	-	3.48:1	
Method of synthesis	-	polymerization occurs in two stages: in the first stage, low molecular ester is produced followed by polycondensation, which produces high molecular weight polymer	Fink, J K, High Performance Polymers, William Andrew, 2008.
Temperature of polymerization	°C	280-300	
Pressure of polymerization	Pa	133	
Catalyst	-	antimony trioxide	
STRUCTURE			
Crystallinity	%	1-4.17 (amorphous); 6.76-49.6 (annealed at 123-170°C for various times); 31-38 (draw ratio 3.6-6.1); 50.6 (biaxially oriented); 50.8-56.5 (fibers containing 5% TLCP); 62.5-87.2 (high pressure crystallized)	Scott, A; Hakme, C; Stevenson, I; Voice, A, Macromol. Symp., 230, 78-86, 2005; Zegnini, B; Boudou, L; Martinez-Vega, J, J. Appl. Sci., 8, 7, 1206-13, 2008; Khemici, M W; Gourari, A; Douliche, N, Int. J. Polym. Anal. Charact., 14, 322-35, 2009; Li, L; Wang, C; Huang, R; Zhang, L; Hong, S, Polymer, 8867-72, 2001.
Cell type (lattice)	-	triclinic	
Cell dimensions	nm	a:b:c=0.651:0.575:1.32 (α -form); a:b:c=0.926:1.559:1.273 (β -form)	Zhang, Y; Mukoyama, S; Hu, Y; Yan, C; Ozaki, Y; Takahashi, I, Macromolecules, 40, 4009-15, 2007.
Unit cell angles	degree	α : β : γ =81:114:100 (α -form); α : β : γ =121.6:95.57:122.52 (β -form)	Zhang, Y; Mukoyama, S; Hu, Y; Yan, C; Ozaki, Y; Takahashi, I, Macromolecules, 40, 4009-15, 2007.

PEN poly(ethylene 2,6-naphthalate)

PARAMETER	UNIT	VALUE	REFERENCES
Number of chains per unit cell	-	1	
Polymorphs	-	α , β	Ulcer, Y; Cakmak, M, Polymer, 38, 2907-10, 1997.
Chain conformation	-	nearly planar	
Entanglement molecular weight	dalton, g/mol, amu	1,810; 25,600	Yi, J H; Won, H J; Dong, I Y, Polym. Bull., 39, 2, 257-63, 1997; Barany, T; Czigany, T; Karger-Kotsis, J, Prog. Polym. Sci., 35, 1257-87, 2010.
Rapid crystallization temperature	°C	198-203	
Avrami constants, k/n	-	2.8-3.0	Wu, T-M; Liu, C-Y, Polymer, 5621-29, 2005.
COMMERCIAL POLYMERS			
Some manufacturers	-	Honeywell; Teijin	
Trade names	-	Pentex; Teonex	
PHYSICAL PROPERTIES			
Density at 20°C	g cm ⁻³	1.33-1.36; 1.325 (amorphous); 1.407 (crystalline)	
Refractive index, 20°C	-	1.50-1.65	
Birefringence	-	0.001-0.0018	Suzuki, A; Tojyo, M, Eur. Polym. J., 2922-27, 2007.
Transmittance	%	84	
Melting temperature, DSC	°C	261-290	
Thermal expansion coefficient, 23-80°C	°C ⁻¹	4.4E-5	
Glass transition temperature	°C	117-122	
Heat of fusion	kJ mol ⁻¹	9.2	
Long term service temperature	°C	155	
Enthalpy of melting	J g ⁻¹	54.3-66.4 (high pressure crystallization)	Li, L; Wang, C; Huang, R; Zhang, L; Hong, S, Polymer, 8867-72, 2001.
Dielectric constant at 100 Hz/1 MHz	-	3.2	
Dissipation factor at 1 MHz	E-4	48	
Volume resistivity	ohm-m	1E13	
Surface resistivity	ohm	1E14	
Electric strength K20/P50, d=0.60.8 mm	kV mm ⁻¹	160	
Coefficient of friction	-	0.27	
Permeability to carbon dioxide, 25°C	cm ³ cm cm ⁻² s ⁻¹ Pa ⁻¹ x 10 ¹²	0.01	
Permeability to oxygen, 25°C	cm ³ cm cm ⁻² s ⁻¹ Pa ⁻¹ x 10 ¹²	0.006	
Permeability to water vapor, 25°C	cm ³ cm cm ⁻² s ⁻¹ Pa ⁻¹ x 10 ¹²	40	

PEN poly(ethylene 2,6-naphthalate)

PARAMETER	UNIT	VALUE	REFERENCES
MECHANICAL & RHEOLOGICAL PROPERTIES			
Tensile strength	MPa	60-68	
Tensile modulus	MPa	2,000	
Elongation	%	250-340	
Flexural strength	MPa	99.5	
Flexural modulus	MPa	2,500	
Young's modulus	MPa	2,850	Caligiuri, L; Stagnaro, P; Valenti, B; Canalini, G, Eur. Polym. J., 45, 217-25, 2009.
Izod impact strength, unnotched, 23°C	J m ⁻¹	420	
Shrinkage	%	0.8	
Intrinsic viscosity, 25°C	dl g ⁻¹	0.59	
Melt viscosity, shear rate=1000 s ⁻¹	Pa s	950	Kim, S Y; Kim, S H; Lee, S H; Youn, J R, Composites: Part A, 40, 607-12, 2009.
Melt index, 300°C/3.8 kg	g/10 min	2.5	Kim, S Y; Kim, S H; Lee, S H; Youn, J R, Composites: Part A, 40, 607-12, 2009.
CHEMICAL RESISTANCE			
Acid dilute/concentrated	-	good/poor	
Alcohols	-	good	
Alkalis	-	good	
Aromatic hydrocarbons	-	good	
Greases & oils	-	good	
Halogenated hydrocarbons	-	poor	
Ketones	-	good	
Good solvent	-	phenol/o-chlorobenzene	
FLAMMABILITY			
Ignition temperature	°C	>400	
Autoignition temperature	°C	587	
Char at 500°C	%	18.2	Lyon, R E; Walters, R N, J. Anal. Appl. Pyrolysis, 71, 27-46, 2004.
Heat of combustion	J g ⁻¹	25,920	Walters, R N; Hacket, S M; Lyon, R E, Fire Mater., 24, 5, 245-52, 2000.
UL rating	-	V-2	
WEATHER STABILITY			
Spectral sensitivity	nm	290-390	
Activation wavelengths	nm	370-380	
Excitation wavelengths	nm	330; 375	
Emission wavelengths	nm	435; 435; 580	
Important initiators and accelerators	-	ferrocene, cobalt octoates and naphthenates, compounds containing aromatic keto-ester groups	
Products of degradation	-	radicals, crosslinks, hydroperoxides, hydroxyl and carbonyl groups, CO, CO ₂	

PEN poly(ethylene 2,6-naphthalate)

PARAMETER	UNIT	VALUE	REFERENCES
Stabilizers	-	<p>UVA: 2-hydroxy-4-octyloxybenzophenone; 2-hydroxy-4-methoxybenzophenone; 2,4-dihydroxybenzophenone; 2,2',4,4'-tetrahydroxybenzophenone; 2,2'-dihydroxy-4-methoxybenzophenone; 2-(2H-benzotriazol-2-yl)-p-cresol; 2-benzotriazol-2-yl-4,6-di-tert-butylphenol; 2-(2H-benzotriazole-2-yl)-4,6-di-tert-pentylphenol; 2-(2H-benzotriazole-2-yl)-4-(1,1,3,3-tetraethylbutyl)phenol; 2-(2H-benzotriazol-2-yl)-4-bis(1-methyl-1-phenylethyl)phenol; 2,2'-methylenebis(6-(2H-benzotriazol-2-yl)-4-1,1,3,3-tetramethylbutyl)phenol; 2-(2H-benzotriazol-2-yl)-6-dodecyl-4-methylphenol, branched & linear; 2-(2H-benzotriazol-2-yl)-4,6-bis(1-methyl-1-phenylethyl)phenol; 2,4-di-tert-butyl-6-(5-chloro-2H-benzotriazole-2-yl)-phenol; 2-(3-sec-butyl-5-tert-butyl-2-hydroxyphenyl)benzotriazole; 2-[4-[(2-hydroxy-3-(2'-ethyl)hexyl)oxy]-2-hydroxyphenyl]-4,6-bis(2,4-dimethylphenyl)-1,3,5-triazine; 2-(4,6-diphenyl-1,3,5-triazin-2-yl)-5-hexyloxy-phenol; 2-[4,6-bis(2,4-dimethylphenyl)-1,3,5-triazin-2-yl]-5-(octyloxy)phenol; (2-ethylhexyl)-2-cyano-3,3-diphenylacrylate; 1,3-bis-[(2'-cyano-3',3'-diphenylacryloyl)oxy]-2,2-bis-[(2'-cyano-3',3'-diphenylacryloyl)oxy]methyl]-propane; propane-dioic acid, [(4-methoxyphenyl)-methylene]-dimethyl ester; 2,2'-(1,4-phenylene)bis[4H-3,1-benzoxazin-4-one]; Screener: carbon black, zinc oxide; Acid scavenger: hydrotalcite; HAS: 1,3,5-triazine-2,4,6-triamine, N,N''[1,2-ethane-diyl-bis[[4,6-bis[butyl(1,2,6,6-pentamethyl-4-piperidinyl)amino]-1,3,5-triazine-2-yl]imino]-3,1-propanediyl]bis[N',N''-dibutyl-N',N''-bis(1,2,2,6,6-pentamethyl-4-piperidinyl)-]; decanedioic acid, bis(2,2,6,6-tetramethyl-1-(octyloxy)-4-piperidinyl)ester, reaction products with 1,1-dimethylethylhydroperoxide and octane; bis(1,2,2,6,6-pentamethyl-4-piperidyl)sebacate + methyl-1,2,2,6,6-pentamethyl-4-piperidyl sebacate; alkenes, C20-24-.alpha.-, polymers with maleic anhydride, reaction products with 2,2,6,6-tetramethyl-4-piperidinamine; 1,6-hexanediamine, N,N'-bis(2,2,6,6-tetramethyl-4-piperidinyl)-, polymers with 2,4-dichloro-6-(4-morpholinyl)-1,3,5-triazine; 1,6-hexanediamine, N,N'-bis(2,2,6,6-tetramethyl-4-piperidinyl)-, polymers with morpholine-2,4,6-trichloro-1,3,5-triazine reaction products, methylated; Phenolic antioxidants: ethylene-bis(oxyethylene)-bis(3-(5-tert-butyl-4-hydroxy-m-tolyl)-propionate); N,N'-hexane-1,6-diylbis(3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionamide)); 3,3',3',5,5',5'-hexa-tert-butyl-a,a',a'-(mesitylene-2,4,6-triyl)tri-p-cresol; 1,3,5-tris(3,5-di-tert-butyl-4-hydroxybenzyl)-1,3,5-triazine-2,4,6-(1H,3H,5H)- trione; Phosphite: bis-(2,4-di-t-butylphenol) pentaerythritol diphosphite; tris (2,4-di-tert-butylphenyl)phosphite; phosphoric acid, (2,4-di-butyl-6-methylphenyl)ethylester; distearyl pentaerythritol diphosphite; Optical brightener: 2,2'-(2,5-thiophenediyl)bis(5-tert-butylbenzoxazole)</p>	
TOXICITY			
Carcinogenic effect	-	not listed by ACGIH, NIOSH, NTP	
Mutagenic effect	-	none	
Teratogenic effect	-	none	
PROCESSING			
Typical processing methods	-	extrusion, injection molding, spinning	
Additives used in final products	-	Antiblocking: calcium carbonate, diatomaceous earth, silicone fluid, spherical silicone resin, synthetic silica; Release: calcium stearate, fluorine compounds, glycerol bistearate, pentaerythritol ester, silane modified silica, zinc stearate; Slip: spherical silica, silicone oil	

PEN poly(ethylene 2,6-naphthalate)

PARAMETER	UNIT	VALUE	REFERENCES
Applications	-	fibers, magnetic recording media, solar cells	
Outstanding properties	-	thermal and mechanical properties	
BLENDS			
Suitable polymers	-	LCP, PET, PBT, PA6,6, HDPE, PTT, PC	
Compatibilizers	-	ethylene/methyl acrylate copolymer compatibilizes blend with HDPE	
ANALYSIS			
FTIR (wavenumber-assignment)	cm ⁻¹ /-	C=O – 1729; CH ₂ <i>trans</i> - 1332; C-O <i>gauche</i> – 1092; crystalline – 1004, 838, 814	Zhang, Y; Mukoyama, S; Hu, Y; Yan, C; Ozaki, Y; Takahashi, I, <i>Macromolecules</i> , 40, 4009-15, 2007.
Raman (wavenumber-assignment)	cm ⁻¹ /-	<i>gauche</i> – 1107; <i>trans</i> – 1098	Schoukens, G; De Clerck, K, <i>Polymer</i> , 46, 845-57, 2005.
NMR (chemical shifts)	ppm	H NMR: ethylene protons – 4.86; methylene protons – 4.45	Woo, E M; Hou, S-S; Huang, D-H; Lee, L-T, <i>Polymer</i> , 46, 7425-35, 2005.
x-ray diffraction peaks	degree	23.3-23.4; 26.8-27.0; 15.6	Zhang, Y; Mukoyama, S; Hu, Y; Yan, C; Ozaki, Y; Takahashi, I, <i>Macromolecules</i> , 40, 4009-15, 2007.