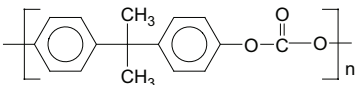
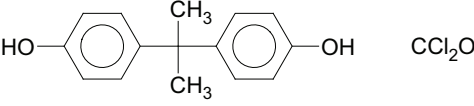


# PC polycarbonate

PARAMETER	UNIT	VALUE	REFERENCES
<b>GENERAL</b>			
Common name	-	polycarbonate	
IUPAC name	-	poly(oxy-carbonyloxy-1,4-phenylene(dimethylmethylen)-1,4-phenylene]	
ACS name	-	carbonic acid, polymer with 4,4'-(1-methylethylidene) bis[phenol]; polycarbonates	
Acronym	-	PC	
CAS number	-	25037-45-0; 25766-59-0	
RTECS number	-	TR1580150	
Formula			
<b>HISTORY</b>			
Person to discover	-	Hermann Schnell	
Date	-	1953; 1958	
Details	-	Bayer chemist synthesized polycarbonate in the first attempt; the experiment was based on analysis of previous research and selection of right building blocks; in order to succeed with implementation, he had to overcome scepticism of his peers that such reaction and outcome are possible; polymer was patented immediately but production begun in 1958	
<b>SYNTHESIS</b>			
Monomer(s) structure	-		
Monomer(s) CAS number(s)	-	80-05-7; 75-44-5	
Monomer(s) molecular weight(s)	dalton, g/mol, amu	228.29; 98.92	
Monomer(s) expected purity(ies)	%	98; 99	
Method of synthesis	-	Bisphenol A is treated with NaOH, which is then reacted with phosgene. It can also be manufactured by transesterification of bisphenol A with diphenyl carbonate.	
Temperature of polymerization	°C	30-40 (polycondensation); 160-240 (transesterification)	Couper, J R; Penney, W R; Fair, J R; Walas, S M, Chemical Equipment, 2nd Ed., Elsevier, 2010, pp. 581-640; Kim, J; Kim, Y J; Kim, J-D; Ahmed, T S; Dong, L B; Roberts, G W; Oh, S-G, Polymer, 2520-26, 2010.
Time of polymerization	h	0.25-4 (polycondensation)	
Pressure of polymerization	Pa	atmospheric	
Catalyst	-	benzyltriethylammonium chloride (polycondensation); LiOH (transesterification)	Couper, J R; Penney, W R; Fair, J R; Walas, S M, Chemical Equipment, 2nd Ed., Elsevier, 2010, pp. 581-640; Kim, J; Kim, Y J; Kim, J-D; Ahmed, T S; Dong, L B; Roberts, G W; Oh, S-G, Polymer, 2520-26, 2010.
Number average molecular weight, $M_n$	dalton, g/mol, amu	17,500-41,300	

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PARAMETER	UNIT	VALUE	REFERENCES
Mass average molecular weight, $M_w$	dalton, g/mol, amu	19,000-56,000	
Polydispersity, $M_w/M_n$	-	1.3-3.2	
Molar volume at 298K	cm <sup>3</sup> mol <sup>-1</sup>	calc.=213.8; exp.=211.9	
Van der Waals volume	cm <sup>3</sup> mol <sup>-1</sup>	calc.=136.21; exp.=138.36	
Molecular cross-sectional area, calculated	cm <sup>2</sup> x 10 <sup>-16</sup>	19.8	
Radius of gyration	nm	13	Fornes, T D; Baur, J W; Sabba, Y; Thomas, E L, Polymer, 47, 1704-14, 2006.
STRUCTURE			
Crystallinity	%	typically amorphous because of its rigid backbone; 20-42	Farmer, R, A Study of Crystallization in Bisphenol A Polycarbonate. Dissertation, Virginia Polytechnic Institute, 2001; Kim, J; Kim, Y J; Kim, J-D; Ahmed, T S; Dong, L B; Roberts, G W; Oh, S-G, Polymer, 2520-26, 2010.
Entanglement molecular weight	dalton, g/mol, amu	calc.=1,734-2,495; exp.=2,495-4,800	
Lamellae thickness	nm	3.18-5.39	Farmer, R, A Study of Crystallization in Bisphenol A Polycarbonate. Dissertation, Virginia Polytechnic Institute, 2001.
COMMERCIAL POLYMERS			
Some manufacturers	-	Bayer; Sabic	
Trade names	-	Makrolon; Lexan	
PHYSICAL PROPERTIES			
Density at 20°C	g cm <sup>-3</sup>	1.19-1.22; 1.04 (melt); 1.25-1.52 (10-40% glass fiber)	
Bulk density at 20°C	g cm <sup>-3</sup>	0.66 (pellets)	
Refractive index, 20°C	-	calc.=1.5773-1.587; exp.=1.586-1.587	
Birefringence	-	-0.001 (surface) to 0.001 (bulk)	Lin, T H; Isayev, A I, Antec, 1664-68, 2006.
Transmittance	%	82-91	
Haze	%	<0.8 to 3	
Melting temperature, DSC	°C	255-267	
Storage temperature (max)	°C	93	
Decomposition onset temperature	°C	420	
Thermal expansion coefficient, -40 to 95°C	°C <sup>-1</sup>	6.0-7.5E-5; 1.6-6.5E-5 (10-40% glass fiber)	
Thermal conductivity, melt	W m <sup>-1</sup> K <sup>-1</sup>	0.19-0.24; 0.2-0.22 (10-40% glass fiber)	
Glass transition temperature	°C	calc.=134-158; exp.=137-154	
Specific heat capacity	J K <sup>-1</sup> kg <sup>-1</sup>	1,200; 1,040-1,210 (10-40% glass fiber)	
Heat of fusion	kJ kg <sup>-1</sup>	100-115 (crystal); 22.95-23.11 (heat to melt)	DeLassus, P T; Landes, B G; Harris, L M, Antec, 1636-39, 1997.

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PARAMETER	UNIT	VALUE	REFERENCES
Maximum service temperature	°C	-40 to 130	
Temperature index (50% tensile strength loss after 20,000 h/5000 h)	°C	120	
Heat deflection temperature at 0.45 MPa	°C	133-166; 141-154 (10-40% glass fiber)	
Heat deflection temperature at 1.8 MPa	°C	119-156; 135-146 (10-40% glass fiber)	
Vicat temperature VST/A/50	°C	138-150; 144-149 (10-35% glass fiber)	
Vicat temperature VST/B/50	°C	144-170; 154 (10-40% glass fiber)	
Hansen solubility parameters, $\delta_D$ , $\delta_P$ , $\delta_H$	MPa <sup>0.5</sup>	19.6, 8.8, 5.7	
Interaction radius		10.2	
Hildebrand solubility parameter	MPa <sup>0.5</sup>	22.2	
Surface tension	mN m <sup>-1</sup>	calc.=33.0-37.9; exp.=28.4-42.9	Liao, C-C; Wang, C-C; Shih, K-C; Chen, C-Y, Eur. Polym. J., 47, 911-24, 2011.
Dielectric constant at 100 Hz/1 MHz	-	3.2/2.9	
Relative permittivity at 100 Hz	-	2.9-3.2; 3.1-3.6 (10-40% glass fiber)	
Relative permittivity at 1 MHz	-	2.8-3.1; 3.0-3.6 (10-40% glass fiber)	
Dissipation factor at 100 Hz	E-4	5-310; 8-13 (10-40% glass fiber)	
Dissipation factor at 1 MHz	E-4	90-120; 67-90 (10-40% glass fiber)	
Volume resistivity	ohm-m	1E12 to 1E15	
Surface resistivity	ohm	1E15 to 1E17	
Electric strength K20/P50, d=0.60.8 mm	kV mm <sup>-1</sup>	15-67; 18-36 (10-40% glass fiber)	
Comparative tracking index, CTI, test liquid A	-	200-250; 175 (10-35% glass fiber)	
Comparative tracking index, CTIM, test liquid B	-	125M	
Coefficient of friction	ASTM D1894	0.21 (chrome steel); 0.41-0.54 (aluminum)	Maldonado, J E, Antec, 3431-35, 1998.
Permeability to nitrogen, 25°C	cm <sup>3</sup> m <sup>-2</sup> 24 h <sup>-1</sup> bar <sup>-1</sup>	130 (100 µm film), 510 (25.4 µm film)	
Permeability to oxygen, 25°C	cm <sup>3</sup> m <sup>-2</sup> 24 h <sup>-1</sup> bar <sup>-1</sup>	700 (100 µm film), 2,760 (25.4 µm film)	
Permeability to water vapor, 25°C	g m <sup>-2</sup> 24 h <sup>-1</sup> bar <sup>-1</sup>	15	
Contact angle of water, 20°C	degree	81.3-84.0	
Surface free energy	mJ m <sup>-2</sup>	42.3	
Speed of sound	m s <sup>-1</sup>	38	
Acoustic impedance		2.69-2.77	
Attenuation	dB cm <sup>-1</sup> , 5 MHz	22.1-24.9	

# PC polycarbonate

PARAMETER	UNIT	VALUE	REFERENCES
<b>MECHANICAL &amp; RHEOLOGICAL PROPERTIES</b>			
Tensile strength	MPa	55-88; 45-158 (10-40% glass fiber)	Chang, M C O; Garrett, P D, Antec, 2588-93, 1996.
Tensile modulus	MPa	2,200-3,100; 3,800-9,400 (10-35% glass fiber)	
Tensile stress at yield	MPa	57-74	Chang, M C O; Garrett, P D, Antec, 2588-93, 1996.
Tensile creep modulus, 1000 h, elongation 0.5 max	MPa	1,700-1,900; 2,900-8,500 (10-35% glass fiber)	
Elongation	%	66-140; 1.8-15 (10-40% glass fiber)	Chang, M C O; Garrett, P D, Antec, 2588-93, 1996.
Tensile yield strain	%	5.7-7; 8 (10-40% glass fiber)	
Flexural strength	MPa	94-120; 103-186 (10-40% glass fiber)	
Flexural modulus	MPa	2,220-2,600; 3,440-9,600 (10-40% glass fiber)	
Elastic modulus	MPa	1,600	
Compressive strength	MPa	70	
Young's modulus	MPa	2,390-2,600	Chang, M C O; Garrett, P D, Antec, 2588-93, 1996.
Charpy impact strength, unnotched, 23°C	kJ m <sup>-2</sup>	no break; 40-150 (10-35% glass fiber)	
Charpy impact strength, unnotched, -30°C	kJ m <sup>-2</sup>	no break	
Charpy impact strength, notched, 23°C	kJ m <sup>-2</sup>	11-80; 8-12 (10-35% glass fiber)	
Charpy impact strength, notched, -30°C	kJ m <sup>-2</sup>	9-14	
Izod impact strength, unnotched, 23°C	J m <sup>-1</sup>	12-90 to NB; 1280-2140 (10-40% glass fiber)	
Izod impact strength, notched, 23°C	J m <sup>-1</sup>	12-736; 8-133 (10-40% glass fiber)	
Izod impact strength, notched, -30°C	J m <sup>-1</sup>	55-618	
Shear modulus	MPa	805	Ozcelik, B; Sonat, I, Mater. Design, 30, 367-75, 2009.
Abrasion resistance (ASTM D1044)	mg/1000 cycles	11 (10-40% glass fiber)	
Poisson's ratio	-	calc.=0.424; exp.=0.401-0.420	Lin, T H; Isayev, A I, Antec, 1664-68, 2006.
Rockwell hardness	-	L89; M85, R124 (10-40% glass fiber)	
Ball indentation hardness at 358 N/30 S (ISO 2039-1)	MPa	116	
Shrinkage	%	0.4-0.9; 0.2-0.55 (10-35% glass fiber)	
Melt volume flow rate (ISO 1133, procedure B), 300°C/1.2 kg	cm <sup>3</sup> /10 min	1.25-36	
Pressure coefficient of melt viscosity, b	G Pa <sup>-1</sup>	26.6	Aho, J; Syrjala, S, J. Appl. Polym. Sci., 117, 1076-84, 2010.
Melt index, 300°C/1.2 kg	g/10 min	6-80	
Water absorption, equilibrium in water at 23°C	%	0.12-0.40; 0.23 (10-40% glass fiber)	
Moisture absorption, equilibrium 23°C/50% RH	%	0.09-0.3	

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PARAMETER	UNIT	VALUE	REFERENCES
<b>CHEMICAL RESISTANCE</b>			
Acid dilute/concentrated	-	good/poor	
Alcohols	-	good	
Alkalis	-	good-poor	
Aliphatic hydrocarbons	-	good	
Aromatic hydrocarbons	-	poor	
Esters	-	poor	
Greases & oils	-	good-poor	
Halogenated hydrocarbons	-	poor	
Ketones	-	poor	
⊖ solvent, ⊖-temp.=170°C	-	n-butyl benzyl ether	
Good solvent	-	acetophenone (hot), aniline (hot), benzene (hot), chloroform, cresol, 1,2-dichloroethane, methylene chloride	
Non-solvent	-	amyl alcohol, ethylene glycol, heptane, isopropyl alcohol	
Chemicals causing environmental stress cracking	-	acetone, benzyl alcohol, carbon tetrachloride, cyclohexanone, nitrobenzene	Wang, H T; Pan, Q G; Du, Q C; Li, Y Q, Polym. Test., 22, 125-28, 2003.
Effect of EtOH sterilization (tensile strength retention)	%	98-100	Navarrete, L; Hermanson, N, Antec, 2807-18, 1996.
<b>FLAMMABILITY</b>			
Ignition temperature	°C	480	
Autoignition temperature	°C	550	
Limiting oxygen index	% O <sub>2</sub>	25-30; 30-43 (flame retardant grades)	
Minimum ignition energy	J	0.025	
Heat release	kW m <sup>-2</sup>	479-548; 124-385 (with fire retardant)	Yu, B; Liu, M; Lu, L; Dong, X; Gao, W; Tang, K, Fire Mater., 34, 251-61, 2010.
NBS smoke chamber	Ds	190	Padey, D; Walling, J; Wood A, Polymers in Defence and Aerospace 2007, Rapra, 2007, paper 15.
Burning rate (Flame spread rate)	mm min <sup>-1</sup>	passed	
Char at 500°C	%	21.7	Lyon, R E; Walters, R N, J. Anal. Appl. Pyrolysis, 71, 27-46, 2004.
Heat of combustion	J g <sup>-1</sup>	31,060-31,530	Walters, R N; Hacket, S M; Lyon, R E, Fire Mater., 24, 5, 245-52, 2000.
Volatile products of combustion	-	carbon monoxide, carbon dioxide, bisphenol A, diphenyl carbonate, phenol and phenol derivatives. Traces of aliphatic and aromatic hydrocarbons, aldehydes and acids.	
UL rating	-	HB to V-2; V-0 (some flame retardant grades); HB to V-0 (10-35% glass fiber)	
<b>WEATHER STABILITY</b>			
Spectral sensitivity	nm	<275 (completely absorbed); 260-300 (photo-Fries rearrangement); 280-305; 330-360	
Activation wavelengths	nm	290-320; 310 (chain scission), 330-360	
Important initiators and accelerators	-	4-hydroxystilbene; products of thermal degradation; bisphenol A, stilbene-like structures, water, bis(3-hydroxyphenyl)ether structures in main chain, some inorganic pigments	

PARAMETER	UNIT	VALUE	REFERENCES
<b>Products of degradation</b>	-	photo-Fries rearrangement; chain scissions, crosslinks, free radicals, hydroxyl groups, ethers, unsaturations (photolysis); chain scissions, hydroperoxides, free radicals, hydroxyl groups, carbonyl groups (photooxidation)	
<b>Stabilizers</b>	-	UVA: 2-hydroxy-4-octyloxybenzophenone; 2,2',4,4'-tetrahydroxybenzophenone; 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)-4,6-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-(2'-hydroxy-5'-methacryloxyethylphenyl)-2H-benzotriazole; 2-(2H-benzotriazol-2-yl)-4,6-bis(1-methyl-1-phenylethyl)phenol; 2-(3-sec-butyl-5-tert-butyl-2-hydroxyphenyl)benzotriazole; reaction product of methyl 3(3-(2H-benzotriazole-2-yl)-5-t-butyl-4-hydroxyphenyl propionate/PEG 300; 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; 1,3-bis-[(2'-cyano-3',3'-diphenylacryloyl)oxy]-2,2-bis-[(2'-cyano-3',3'-diphenylacryloyl)oxy]methyl)-propane; propanedioic acid, [(4-methoxyphenyl)-methylene]-dimethyl ester; 2,2'-(1,4-phenylene)bis[4H-3,1-benzoxazin-4-one]; Screener: zinc oxide; Phenolic antioxidant: 2-(1,1-dimethylethyl)-6-[[3-(1,1-dimethylethyl)-2-hydroxy-5-methylphenyl] methyl-4-methylphenyl acrylate; Phosphite: tris (2,4-di-tert-butylphenyl) phosphite; isodecyl diphenyl phosphite; di(p-butoxyphenyl) cyclohexylphosphine oxide; Optical brightener: 2,2'-(2,5-thiophenediyl)bis(5-tert-butylbenzoxazole); 2,2'-(1,2-ethylenediyl-di-4,1-phenylene)bisbenzoxazole; Plasticizer: dicyclohexyl phthalate (reduces yellowing on exposure to gamma radiation)	
<b>Results of exposure</b>		yellowness index: 45 after 60 month exposure in Florida without stabilization and 22 after 60 month exposure in Florida with stabilization; 13 and 26 after 120 month exposure in Engerfeld, Germany with and without stabilization, respectively	
<b>Low earth orbit erosion yield</b>	cm <sup>3</sup> atom <sup>-1</sup> x 10 <sup>-24</sup>	4.29	Waters, D L; Banks, B A; De Groh, K K; Miller, S K R; Thorson, S D, High Performance Polym., 20, 512-22, 2008.
<b>BIODEGRADATION</b>			
<b>Colonized products</b>		compact disks, medical devices	
<b>Typical biodegradants</b>	-	microorganisms producing esterase are capable of damage; marine environment	Artham, T; Doble, M, J. Polym. Environ., 17, 170-80, 2009.
<b>Stabilizers</b>	-	silver-based biocides	
<b>TOXICITY</b>			
<b>NFPA: Health, Flammability, Reactivity rating</b>	-	0/1/0	
<b>Carcinogenic effect</b>	-	not listed by ACGIH, NIOSH, NTP	
<b>OSHA</b>	mg m <sup>-3</sup>	5 (respirable), 15 (total)	
<b>Acceptable daily intake</b>	µg kg <sup>-1</sup> body weight day <sup>-1</sup>		
<b>Oral rat, LD<sub>50</sub></b>	mg kg <sup>-1</sup>	>10,000	
<b>Skin rabbit, LD<sub>50</sub></b>	mg kg <sup>-1</sup>	>2,000	

# PC polycarbonate

PARAMETER	UNIT	VALUE	REFERENCES
<b>ENVIRONMENTAL IMPACT</b>			
Aquatic toxicity, <i>Daphnia magna</i> , LC <sub>50</sub> * 48 h	mg l <sup>-1</sup>	5,000	Lither, D; Damberg, J; Dave, G; Larsson, A, Chemosphere, 74, 1198-1200, 2009.
Cradle to grave non-renewable energy use	MJ/kg	111	
Cradle to pellet greenhouse gasses	kg CO <sub>2</sub> kg <sup>-1</sup> resin	7.8	
<b>PROCESSING</b>			
Typical processing methods	-	blow molding, calendering, electrospinning, extrusion, gas-assisted injection molding, injection molding, solution casting, thermoforming	
Preprocess drying: temperature/time/residual moisture	°C/h/%	120-135/2-12/0.02	
Processing temperature	°C	280-355; 310-340 (10-40% glass fiber)	
Processing pressure	MPa	0.3-0.7 (back pressure)	
Additives used in final products	-	Fillers: boric oxide, glass beads, carbon black and graphite fibers for EMI shielding, glass fiber, graphite, molybdenum sulfide, nanosilica, nickel-coated graphite fibers, PTFE, single-walled carbon nanotubes, steel fibers, titanium dioxide, wollastonite; Plasticizers: dibutyl phthalate, dioctyl phthalate, dicyclohexyl phthalate, mineral oil, pentaerythritol tetraborate, trimellitic acid tridecyloctyl ester, tritolyl phosphate, tetra-ethylene glycol dimethyl ether, tri-(2-ethylhexyl) phosphate; Antistatics: carbon black, carbon nanotubes, copper oxide, glycerol mono-iso-stearate, indium tin oxide, nickel-coated carbon fiber, polyetheresteramide, polyoxyethylene fatty acid ester; Antiblocking: amorphous silica, calcium carbonate, dimethylsiloxane grafting, siloxane particles; Release: glycerol monostearate, pentaerythritol tetrastearate, siloxane, zinc stearate; impact modifier; UV stabilizers; release agents	
Applications	-	bearings, blood collector containers, camera components, computer printers, copying machines, corrective eyeglasses, dental applications, data storage (CD, DVD, etc.), dinnerware, drinking cups, disposable syringes, head lamp covers and housings, gears, glazing, goggles, golf tees, guide pins, helmets, instrument panels, laminated walls, lenses, medical tubing, microfibers, needles syringes, optical lenses, pace-maker components, projection screens, rollers, roofing, safety glasses, skylights, speedometer needles, solar modules, tool boxes, toys, water bottles, windows, windscreens	
<b>BLENDS</b>			
Suitable polymers	-	ABS, PBT, PET, PHEMA, PLA, PVDF	
<b>ANALYSIS</b>			
FTIR (wavenumber-assignment)	cm <sup>-1</sup> /-	C-H – 3047, 2877; C-O-C – 989; C=O – 1778	Abdel-Salam, M H; Nouh, S A; Radwan, Y E; Fouad, S S, Mater. Chem. Phys., 127, 305-9, 2011.
Raman (wavenumber-assignment)	cm <sup>-1</sup> /-	C=O – 1769, 1597, 712; CH <sub>3</sub> – 1453	Hoeller, T L, Antec, 3124-30, 2007.