

Handbook OF POLYMERS



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Handbok of Polymers

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Introduction

Polymers selected for this edition of the Handbook of Polymers include all major polymeric materials used by the plastics and other branches of the chemical industry as well as specialty polymers used in the electronics, pharmaceutical, medical, and space fields. Extensive information is provided on biopolymers.

The data included in the Handbook of Polymers come from open literature (published articles, conference papers, and books), literature available from manufacturers of various grades of polymers, plastics, and finished products, and patent literature. The above sources were searched, including the most recent literature. It can be seen from the references that a large portion of the data comes from information published in 2011. This underscores one of the major goals of this undertaking, which is to provide readers with the most up-to-date information.

Frequently, data from different sources vary in a broad range and they have to be reconciled. In such cases, values closest to their average and values based on testing of the most current grades of materials are selected to provide readers with information which is characteristic of currently available products, focusing on the potential use of data in solving practical problems. In this process of verification many older data were rejected unless they have been confirmed by recently conducted studies.

Presentation of data for all polymers is based on a consistent pattern of data arrangement, although, depending on data availability, only data fields which contain actual values are included for each individual polymer. The entire scope of the data is divided into sections to make data comparison and search easy.

The following sections of data are included:

- General
- History
- Synthesis
- Structure
- Commercial polymers
- Physical properties
- Mechanical properties
- Chemical resistance
- Flammability
- Thermal stability
- Weather stability
- Biodegradation
- Toxicity
- Environmental impact
- Processing
- Blends
- Analysis

It can be anticipated from the above breakdown of information that the Handbook of Polymers contains information on all essential data used in practical applications, research, and legislation, providing such data are available for a particular material. In total, over 230 different types of data were searched for each individual polymer. The last number does not include special fields that might be added to characterize the performance of specialty polymers in their applications.

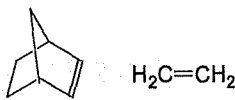
In most cases, the information provided is self-explanatory, considering that each data field is composed of parameter (or measured property), unit, value, and reference. In some cases, different values or a range of values are given. This is to indicate the fact that there is a disagreement in the published data which cannot be reconciled, or that the data falls into a broader range because various grades differ in properties. Utmost care is taken that the specified range contains all grades known from published data. If there are specific grades differing in properties, a set of separate ranges is given in some cases.

After some data, information is given in parenthesis to indicate additional characteristics of tested samples. The usual convention is that the first value given is for pure or typical material, followed by its different modifications (e.g., reinforcements with different fibers or different levels of crystallinity, structure, or different conditions of sample as to its temperature, state, etc.).

The range of molecular weights and related data (e.g., polymerization degree) requires additional explanation. In some cases, the number average molecular weight data do not correspond to mass average molecular data (as could be expected from a given range of polydispersities). This is because these data are given based on values found in literature without any attempts to reconcile them by means of calculation, which seems to be the correct approach because the data strictly reflect values found in the literature, not the results of any approximations which will artificially compare sets of data for materials coming from different experimental or production conditions. This is in agreement with one essential goal of this collection – authenticity of the data selected.

We hope that the results of our thorough search will be useful and that the data will be skillfully applied by users of this book for the benefit of their research and applications.

COC cyclic olefin copolymer

PARAMETER	UNIT	VALUE	REFERENCES
GENERAL			
Common name	-	cyclic olefin copolymer	
CAS name	-	bicyclo[2.2.1]hept-2-ene, polymer with ethene	
Acronym	-	COC	
CAS number	-	26007-43-2	
RETECS number	-	RC0190000	
SYNTHESIS			
Monomer(s) structure	-		
Monomer(s) CAS number(s)	-	498-66-8; 74-85-1	
Monomer(s) molecular weight(s)	dalton, g/mol, amu	94.17; 28.05	
Monomer(s) expected purity(ies)	%	99; 99.95	
Norbornene contents	%	20.2-82	
Temperature of polymerization	°C	80-120	
Time of polymerization	h	60	
Pressure of polymerization	kPa	120-240	Young, M-J; Chang, W-S; Ma, C-C M, Eur. Polym. J., 39, 165-71, 2003.
Catalyst	-	ethylene-bis-(indenyl)zirconium dichloride; metallocene	
Initiation rate constant	mol s ⁻¹	1.94E5	Young, M-J; Chang, W-S; Ma, C-C M, Eur. Polym. J., 39, 165-71, 2003.
Propagation rate constant	mol s ⁻¹	2.804E5, 2.782E5	Young, M-J; Chang, W-S; Ma, C-C M, Eur. Polym. J., 39, 165-71, 2003.
Termination rate constant	mol s ⁻¹	2.4E8	Young, M-J; Chang, W-S; Ma, C-C M, Eur. Polym. J., 39, 165-71, 2003.
Chain transfer rate constant	mol s ⁻¹	4.159E3, 3.471E1	Young, M-J; Chang, W-S; Ma, C-C M, Eur. Polym. J., 39, 165-71, 2003.
Number average molecular weight, M _n	dalton, g/mol, amu	51,000-173,000	
Mass average molecular weight, M _w	dalton, g/mol, amu	41,000-188,000	
Polydispersity, M _w /M _n	-	1.5-4.1	
Polymerization degree (number of monomer units)	-		
Molar volume at 298K	cm ³ mol ⁻¹	51.1-67.5	Poulsen, L; Zebger, I; Klinger, M; Eldrup, M, Sommer-Larse, P; Ogilby, P R, Macromolecules, 36, 7189-98, 2003.
Molar volume at melting point	dcm ³ mol ⁻¹		
Van der Waals volume	cm ³ mol ⁻¹	32.5-46.1	Poulsen, L; Zebger, I; Klinger, M; Eldrup, M, Sommer-Larse, P; Ogilby, P R, Macromolecules, 36, 7189-98, 2003.

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COC cyclic olefin copolymer

PARAMETER	UNIT	VALUE	REFERENCES
Permeability to water vapor, 25°C	g mm m ² day ⁻¹	0.0019-0.035	Poulsen, L; Zebger, I; Klinger, M; Eldrup, M, Sommer-Larse, P; Ogilby, P R, Macromolecules, 36, 7189-98, 2003.
Diffusion coefficient of oxygen	cm ² s ⁻¹ x10 ⁸	2.2-5.8	

MECHANICAL & RHEOLOGICAL PROPERTIES

Tensile strength	MPa	22-72	
Tensile modulus	MPa	1260-3200	
Tensile stress at yield	MPa	37-60	
Elongation	%	1.1-100	
Tensile yield strain	%	6.5	
Flexural strength	MPa	90-110	
Flexural modulus	MPa	2,400-3,200	
Charpy impact strength, 23°C	kJ m ⁻²	13-20	
Charpy impact strength, notched, 23°C	kJ m ⁻²	1.6-2.6	
Izod impact strength, notched, 23°C	J m ⁻¹	25-45	
Ball indentation hardness at 358 N/30 S (ISO 2039-1)	MPa	130-184	
Shrinkage	%	0.1-0.7	
Melt viscosity, shear rate=1000 s ⁻¹	Pa s	100-650	
Melt volume flow rate (ISO 1133, procedure B), 230°C/2.16 kg	cm ³ /10 min	1-9 (extrusion grades); 14-48 (injection molding grades)	
Melt index, 260°C/2.16 kg	g/10 min	2-36	
Water absorption, equilibrium in water at 23°C	%	<0.01	

CHEMICAL RESISTANCE

Acid dilute/concentrated	-	resistant	
Alcohols	-	resistant	
Alkalis	-	resistant	
Aliphatic hydrocarbons	-	non-resistant	
Aromatic hydrocarbons	-	non-resistant	
Esters	-	resistant	
Greases & oils	-	non-resistant	
Halogenated hydrocarbons	-	non-resistant	
Ketones	-	resistant (short chain)	

FLAMMABILITY

Autoignition temperature	°C	445	
UL rating	-	HB	

COC cyclic olefin copolymer

PARAMETER	UNIT	VALUE	REFERENCES
WEATHER STABILITY			
Spectral sensitivity	nm	280-380	Huang, W-J; Chang, F-C, J. Polym. Res., 10, 195-200, 2003. Pu, Q; Oyesanya, O; Thompson, B; Liu, S; Alvarez, J C, Langmuir, 23, 1577-83, 2007.
Activation wavelengths	nm	267	
Activation energy of aging	kJ mol ⁻¹	1,522	
Depth of UV penetration	μm		
Products of degradation	-	chromophores, hydroperoxides, COOH	
Stabilizers	-	antioxidants (e.g. Irganox 1010)	
TOXICITY			
NFPA: Health, Flammability, Reactivity rating	-	1/1/0	
TLV, ACGIH	mg m ⁻³	10; 3 (respirable fraction)	
OSHA	mg m ⁻³	5 (respirable dust); 15 (total dust)	
Oral rat, LD ₅₀	mg kg ⁻¹	3250	
PROCESSING			
Typical processing methods	-	injection molding, extrusion, thermoforming	
Processing temperature	°C	190-240	
Processing pressure	MPa	14 (extrusion); 50-110 (injection pressure)	
Process time	min	15 (injection molding)	
Additives used in final products	-	rheological additives	
Applications	-	bottles, contact lenses, cosmetics, electronics, film, health care, industrial parts, optical parts, pharmaceuticals, packaging, printer toner, sheet	
Outstanding properties	-	high clarity, outstanding moisture barrier, high heat distortion temperature	
BLENDS			
Suitable polymers	-	LLDPE, PC, PP	
ANALYSIS			
FTIR (wavenumber-assignment)	cm ⁻¹ /-	C=O – 1850-1680; C=C – 1680-1590; C-O-C – 1400-1100	Nakade, K; Nagai, Y; Ohishi, F, Polym. Deg. Stab., 95, 2654-58, 2010.

EAA poly(ethylene-co-acrylic acid)

PARAMETER	UNIT	VALUE	REFERENCES
GENERAL			
Common name	-	poly(ethylene-co-acrylic acid)	
ACS name	-	2-propenoic acid, polymer with ethene	
Acronym	-	EAA	
CAS number	-	9010-77-9	
SYNTHESIS			
Monomer(s) structure	-	$\text{H}_2\text{C}=\text{CH}_2 \quad \text{H}_2\text{C}=\text{CH}\overset{\text{O}}{\parallel}\text{COOH}$	
Monomer(s) CAS number(s)	-	74-85-1; 79-10-7	
Monomer(s) molecular weight(s)	dalton, g/mol, amu	28.05; 72.06	
Acrylic acid content	%	5-38	
Aromaticity	%	0-10 of aromatic protons	
Temperature of polymerization	°C	240-300	
Pressure of polymerization	MPa	200-300	
Number average molecular weight, M_n	dalton, g/mol, amu	280-31,000	
Mass average molecular weight, M_w	dalton, g/mol, amu	450-86,000	
Polydispersity, M_w/M_n	-	1.1-3.97	McAlduff, M; Reven, L, Macromolecules, 38, 3745-53, 2005.
STRUCTURE			
Crystallinity	%	8-37	Zhang, J; Chen, S; Su, J; Shi, X; Jin, J; Wang, X; Xu, Z, J. Therm. Anal. Calorim., 97, 959-67, 2009.
Peak crystallization temperature	°C	85-90	
Avrami constants, k/n	-	-3-4	Zhang, J; Chen, S; Su, J; Shi, X; Jin, J; Wang, X; Xu, Z, J. Therm. Anal. Calorim., 97, 959-67, 2009.
COMMERCIAL POLYMERS			
Some manufacturers	-	DOW; DuPont	
Trade names	-	Primacor; Nucrel	
PHYSICAL PROPERTIES			
Density at 20°C	g cm ⁻³	0.92-0.96	
Bulk density at 20°C	g cm ⁻³	0.5-0.6	
Color	-	clear to white to off-white to yellow	
Haze	%	3.7-4	
Gloss, 60°, Gardner (ASTM D523)	%	74-76	
Odor	-	acidic	
Melting temperature, DSC	°C	75-112	
Softening point	°C	92-140	
Thermal degradation	°C	325	
Glass transition temperature	°C	-28 to 86	
Vicat temperature VST/A/50	°C	40-90	

EAA poly(ethylene-co-acrylic acid)

PARAMETER	UNIT	VALUE	REFERENCES
pKa	-	4.25	Laney, K A, Elastic Modulus of Poly(ethylene-co-acrylic acid) Copolymers and Ionomers, Diss., Princeton, May 2010.
Coefficient of friction	-	0.3; 0.15-0.18 (with slip)	Luo, N; Janorkar, A V; Hirt, D E; Husson, S M; Schwark, D W, J. Appl. Polym. Sci., 97, 2242-48, 2005.
Permeability to oxygen, 25°C	cm ³ mm m ⁻² day ⁻¹ atm ⁻¹	180-550	
Permeability to water vapor, 25°C	g mm m ⁻² atm ⁻¹ 24 h ⁻¹	0.0.37-0.44	
MECHANICAL & RHEOLOGICAL PROPERTIES			
Tensile strength	MPa	6.2-24	
Tensile modulus	MPa	22-130	
Tensile stress at yield	MPa	7.2-10	
Elongation	%	390-640	
Flexural modulus	MPa	110	
Young's modulus	MPa	65-115	Valenza, A; Visco, A M; Acierno, D, Polym. Test., 21, 101-9, 2002.
Dart drop impact	g	410	
Elmendorf tear strength	g	270-730	
Shore D hardness	-	50-51	
Melt viscosity, shear rate=1000 s ⁻¹	Pa s	0.93-7	
Melt index, 190°C/2.16 kg	g/10 min	1.5-1300	
CHEMICAL RESISTANCE			
Alkalis	-	good	
Aliphatic hydrocarbons	-	poor	
Aromatic hydrocarbons	-	poor	
FLAMMABILITY			
Ignition temperature	°C	>250 to 340	
BIODEGRADATION			
Stabilizers	-	benzoyl chloride	Matche, R S; Kulkarni, G; Raj B, J. Appl. Polym. Sci., 100, 3063-68, 2006.
TOXICITY			
NFPA: Health, Flammability, Reactivity rating	-	1/1/0; 1/1/0 (HMIS)	
Carcinogenic effect	-	not listed by ACGIH, NIOSH, NTP	
TLV, ACGIH	ppm	2 (acrylic acid)	
OSHA	ppm	10 (acrylic acid)	
Oral rat, LD ₅₀	mg kg ⁻¹	>2,350; >5,000	
Skin rabbit, LD ₅₀	mg kg ⁻¹	>2,000	

EAA poly(ethylene-co-acrylic acid)

PARAMETER	UNIT	VALUE	REFERENCES
PROCESSING			
Typical processing methods	-	cast film, extrusion blown film, extrusion coating, lamination	
Processing temperature	°C	193-288 (extrusion); 305-325 (blown film)	
Additives used in final products	-	Slip: erucamide, grafted 12-aminododecamide	Luo, N; Janorkar, A V; Hirt, D E; Husson, S M; Schwark, D W, J. Appl. Polym. Sci., 97, 2242-48, 2005.
Applications	-	packaging multilayer films, resins for hot-melt adhesives, resins for pressure-sensitive adhesives; products: hot-melt packaging, curtain coating, bookbinding, glue stick, masking tapes, carpet tape, mounting tape, paper, strapping tapes, thermoplastic road marking	
Outstanding properties	-	adhesion, environmental stress cracking resistance, optical properties, strength	
BLENDS			
Suitable polymers	-	PA6, PE, PP, starch	
ANALYSIS			
FTIR (wavenumber-assignment)	cm ⁻¹ /-	OH – 3500; C-H – 2925, 2850, 1450, 1465, 1375; C=O – 1710, 1230-1320; C-C – 940	Valenza, A; Visco, A M; Acierno, D, Polym. Test., 21, 101-9, 2002.

HDPE high density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
GENERAL			
Common name	-	high density polyethylene; poly(ethylene-co-1-hexene); poly(ethylene-co-1-octene)	
IUPAC name	-	polyethene	
Acronym	-	HDPE	
CAS number	-	25213-02-9 (hexene); 26221-73.8 (octene)	
Formula	-	$\text{--}[\text{CH}_2\text{CH}_2]\text{--}_n$	
HISTORY			
Person to discover	-	Karl Ziegler and Giulio Natta; Paul Hogan and Robert Banks	
Date	-	1950, 1951, 1961	
Details	-	Ziegler developed catalyst which permits polymerization at low pressure and Natta explained mechanism; in 1951 Paul Hogan and Robert Banks discovered HDPE; in 1961 Phillips process (commercial process used today) was commercialized	
SYNTHESIS			
Monomer(s) structure	-	$\text{H}_2\text{C}=\text{CH}_2$	
Monomer(s) CAS number(s)	-	74-85-1	
Monomer(s) molecular weight(s)	dalton, g/mol, amu	28.05	
Formulation example	-	selection of chromium/silica catalysts, Ziegler-Natta catalysts, or metallocene catalysts makes it possible to achieve low degree of branching required to obtain high density polyethylene (density >0.94), paraffin or cycloparaffin are used as diluents	
Method of synthesis	-	slurry polymerization or gas-solid polymerization	Wolf, C R; de Carmago Forte, M M; dos Santos, J H Z, Catalysis Today, 107-108, 451-57, 2005.
Temperature of polymerization	°C	80-100 (ZN)	
Pressure of polymerization	MPa	0.1	
Catalyst	-	chromium/silica catalysts, Ziegler-Natta catalysts, or metallocene	
Heat of polymerization	kJ mol ⁻¹	93.6	
Mass average molecular weight, M_w	dalton, g/mol, amu	low – 1,000-100,000 (injection molding); medium – 100,000-180,000 (blow molding, film, pipe, sheet); high – 250,000-750,000 (large part blow molding, high strength thin films, pipe, sheet); extra high – 750,000-1,500,000 (extra large part blow molding)	
Polydispersity, M_w/M_n	-	1 to >10	
Degree of branching	-	5/1000C	
Type of branching	-	1 side branching per 200 atoms	
STRUCTURE			
Crystallinity	%	70-90	
Cell type (lattice)	-	orthorhombic	
Cell dimensions	nm	a:b:c=0.740-0.748:0.493-0.497:0.253-0.255	
Unit cell angles	degree	α : β : γ =90:90:90	
Number of chains per unit cell	-	4	

HDPE high density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
Chain conformation	-	planar zig-zag	
Entanglement molecular weight	dalton, g/mol, amu	800-1100	
Lamellae thickness	nm	0.42-14.1 (film; depending on melt flow rate, melt extension, and annealing temperature)	Lee, S-Y; Park, S-Y; Song, H-S, Polymer, 47, 3540-47, 2006.
Rapid crystallization temperature	°C	114-120; 117 (bimodal)	
COMMERCIAL POLYMERS			
Some manufacturers	-	DOW; ExxonMobil	
Trade names	-	Continuum (bimodal), Dowlax, HDPE , Unival; LDPE, Nexxstar	
PHYSICAL PROPERTIES			
Density at 20°C	g cm ⁻³	0.94-0.965; 0.996-1.0 (crystalline)	
Color	-	white	
Refractive index, 20°C	-	1.54; 1.4261-1.4327 (amorphous); 1.520-1.582 (crystalline)	
Birefringence	-	0.01-0.012 (drawn filaments); 0.005-0.025 (film; depending on melt flow rate, melt extension, and annealing temperature)	Choi, C-H; White, J L, Intl. Polym. Proces., 13, 1, 78-87, 1998; Lee, S-Y; Park, S-Y; Song, H-S, Polymer, 47, 3540-47, 2006.
Haze	%	6	
Gloss, 60°, Gardner (ASTM D523)	%	68	
Odor	-	odorless	
Melting temperature, DSC	°C	125-135; 130 (bimodal)	
Decomposition temperature	°C	>250	
Thermal conductivity, melt	W m ⁻¹ K ⁻¹	0.52-0.55	
Glass transition temperature	°C	-118 to -133	
Heat of fusion	kJ mol ⁻¹	4.14	
Maximum service temperature	°C	>220 (bimodal)	
Long term service temperature	°C	-50 to 82	
Heat deflection temperature at 0.45 MPa	°C	62-90; 68.3 (bimodal)	
Heat deflection temperature at 1.8 MPa	°C	44-65	
Vicat temperature VST/A/50	°C	122-129; 127-131 (bimodal)	
Hildebrand solubility parameter	MPa ^{0.5}	calc.=16.0-16.8; exp.=17.1	
Surface tension	mN m ⁻¹	26.0-28.8	
Dielectric constant at 1000 Hz/1 MHz	-	2.3-2.35/	
Dissipation factor at 1000 Hz	E-4	2	
Volume resistivity	ohm-m	1E13	
Electric strength K20/P50, d=0.60.8 mm	kV mm ⁻¹	17-45	
Arc resistance	s	200-250	
Coefficient of friction	ASTM D1894	0.17 (chrome steel); 0.27-0.33 (aluminum)	Maldonado, J E, Antec, 3431-35, 1998.

HDPE high density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
Permeability to nitrogen, 25°C	cm ³ cm cm ⁻² s ⁻¹ Pa ⁻¹ x 10 ¹²	0.011	
Permeability to oxygen, 25°C	cm ³ cm cm ⁻² s ⁻¹ Pa ⁻¹ x 10 ¹²	0.03	
Permeability to water vapor, 25°C	cm ³ cm cm ⁻² s ⁻¹ Pa ⁻¹ x 10 ¹²	0.9	
Diffusion coefficient of nitrogen	cm ² s ⁻¹ x10 ⁶	0.093	
Diffusion coefficient of oxygen	cm ² s ⁻¹ x10 ⁶	0.17	
Diffusion coefficient of water vapor	cm ² s ⁻¹ x10 ⁶		
Contact angle of water, 20°C	degree	80.5	Daniloska, V; Blazevska-Gilev, J; Dimova, V; Fajgar, R; Tomovska, R, Appl. Surface Sci., 256, 2276-83, 2010.
Speed of sound	m s ⁻¹	40.5	
Acoustic impedance		2.33	

MECHANICAL & RHEOLOGICAL PROPERTIES

Tensile strength	MPa	13.0-51.0; 17.9-29.0 (bimodal)	
Tensile modulus	MPa	500-1,100; 1,120-1,350 (bimodal)	
Tensile stress at yield	MPa	21.4-31.0; 23.5-24.8 (bimodal)	
Tensile creep modulus, 1000 h, elongation 0.5 max	MPa	6-11	
Elongation	%	250-1,200; 600-860 (bimodal)	
Tensile yield strain	%	8.7-15; 3.7-6.3 (bimodal)	
Flexural modulus	MPa	750-1,600; 621-1,680 (bimodal)	
Compressive strength	MPa	20	
Young's modulus	MPa	800	
Izod impact strength, notched, 23°C	J m ⁻¹	20-220; 490 (bimodal)	
Hydrostatic strength, 23°C	MPa	9-12.4 (bimodal)	
Resistance to rapid crack propagation, P _c , 0°C	bar	38.6-45.9 (bimodal)	
Resistance to rapid crack propagation, T _c	°C	-2 to -17 (bimodal)	
Slow crack growth	h	4,000-15,000 (bimodal)	
Shore D hardness	-	57-69; 59 (bimodal)	
Shrinkage	%	1.5-4; 2.84 (across the flow), 1.98 (along the flow)	Chang, T; Faison, E, Polym. Eng. Sci., 41, 5, 703-10, 2001.
Brittleness temperature (ASTM D746)	°C	-20 to -76.1; -60 to -75 (bimodal)	
Melt viscosity, shear rate=1000 s ⁻¹	Pa s	2.57-1630 (133°C); 10.1-64.5 (192°C)	

HDPE high density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
Melt index, 190°C/2.16 kg	g/10 min	10-100 (low M_w); 0.6-10 (medium M_w); 0.06-0.15 (high M_w)	
Water absorption, equilibrium in water at 23°C	%	0.005-0.01	
CHEMICAL RESISTANCE			
Acid dilute/concentrated	-	very good	
Alcohols	-	good	
Alkalis	-	very good	
Aliphatic hydrocarbons	-	poor	
Aromatic hydrocarbons	-	poor	
Esters	-	poor	
Greases & oils	-	good to poor	
Halogenated hydrocarbons	-	poor	
Ketones	-	poor	
⊙ solvent, ⊖-temp.=127, >200, 162, 163	-	biphenyl, dibutyl phthalate, diphenyl ether, p-nonyl phenol	
Good solvent	-	1,2,4-trichlorobenzene, decalin, halogenated hydrocarbons, aliphatic ketones, xylene (all above 60°C)	
Non-solvent	-	most common solvents	
Effect of EtOH sterilization (tensile strength retention)	%	92-96	Navarrete, L; Hermanson, N, Antec, 2807-18, 1996.
FLAMMABILITY			
Ignition temperature	°C	340-343	
Autoignition temperature	°C	350	
Limiting oxygen index	% O ₂	<20	
Heat of combustion	J g ⁻¹	47,740	
Volatile products of combustion	-	CO, CO ₂ , aldehydes, benzene	
UL rating	-	HB	
WEATHER STABILITY			
Spectral sensitivity	nm	<300	
Activation wavelengths	nm	300, 330-360	
Excitation wavelengths	nm	230, 265, 275, 290, 292	
Emission wavelengths	nm	295, 312, 330, 344, 358, 450	
Important initiators and accelerators	-	unsaturations, aromatic carbonyl compounds (deoxyanisoin, dibenzocycloheptadienone, flavone, 4-methoxybenzophenone, 10-thioxanthone), hydrogen bound to tertiary carbon at branching points, aromatic amines, groups formed on oxidation (hydroperoxides, carbonyl, carboxyl, hydroxyl) substituted benzophenones, complexes with ground-state oxygen, quinones (anthraquinone, 2-chloroanthraquinone, 2-tert-butylanthraquinone, 1-methoxyanthraquinone, 2-ethylanthraquinone, 2-methylanthraquinone), transition metal compounds (Ni < Zn < Fe < Co), ferrocene derivatives, titanium dioxide (anatase), ferric stearate, polynuclear aromatic compounds (anthracene, phenanthrene, pyrene, naphthalene)	
Products of degradation	-	free radicals, hydroperoxides, carbonyl groups, chain scission, crosslinking	

HDPE high density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
Stabilizers	-	UVA: 2-hydroxy-4-octyloxybenzophenone; phenol, 2-(5-chloro-2H-benzotriazole-2-yl)-6-(1,1-dimethylethyl)-4-methyl-; 2,2'-methylenebis(6-(2H-benzotriazol-2-yl)-4-1,1,3,3-tetramethylbutyl)phenol; 2,4-di-tert-butyl-6-(5-chloro-2H-benzotriazole-2-yl)-phenol; reaction product of methyl 3-(2H-benzotriazole-2-yl)-5-t-butyl-4-hydroxyphenyl propionate/ PEG 300; 2-[4,6-bis(2,4-dimethylphenyl)-1,3,5-triazin-2-yl]-5-(octyloxy) phenol; Screener: titanium dioxide; zinc oxide; carbon black; Acid scavenger: hydrotalcite; Fiber: carbon nanotube; 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-piperidiny)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-piperidiny)-; bis(1,2,2,6,6-pentamethyl-4-piperidyl)sebacate + methyl-1,2,2,6,6-pentamethyl-4-piperidyl sebacate; 2,2,6,6-tetramethyl-4-piperidiny] stearate; reaction products of N,N'-ethane-1,2-diylbis(1,3-propanediamine), cyclohexane, peroxidized 4-butylamino-2,2,6,6-tetramethylpiperidine and trichloro-1,3,5-triazine; poly[[[6-(1,1,3,3-tetramethylbutyl) amino]-1,3,5-triazine-2,4-diyl][2,2,6,6-tetramethyl-4-piperidiny] imino]-1,6-hexanediyl[2,2,6,6-tetramethyl-4-piperidiny]imino]; 1,6-hexanediamine- N,N'-bis(2,2,6,6-tetramethyl-4-piperidiny)- polymer with 2,4,6-trichloro-1,3,5-triazine, reaction products with N-butyl-1-butanamine an N-butyl-2,2,6,6-tetramethyl-4-piperidinamine; butanedioic acid, dimethylester, polymer with 4-hydroxy-2,2,6,6-tetramethyl-1-piperidine ethanol; 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-piperidiny)-, polymers with morpholine-2,4,6-trichloro-1,3,5-triazine reaction products, methylated; Phenolic antioxidant: 2,6-di-tert-butyl-4-(4,6-bis(octylthio)-1,3,5-triazine-2-ylamino) phenol; pentaerythritol tetrakis(3-(3,5-di-tert-butyl-4-hydroxyphenyl) propionate); octadecyl-3-(3,5-di-tert-butyl-4-hydroxyphenyl)-propionate; 3,3',3',5,5',5'-hexa-tert-butyl-a,a',a'-(mesitylene-2,4,6-triyl)tri-p-cresol; 2-(1,1-dimethylethyl)-6-[[3-(1,1-dimethylethyl)-2-hydroxy-5-methylphenyl] methyl-4-methylphenyl acrylate; 1,3,5-tris(3,5-di-tert-butyl-4-hydroxybenzyl)-1,3,5-triazine-2,4,6-(1H,3H,5H)-trione; 3,4-dihydro-2,5,7,8-tetramethyl-2-(4,8,12-trimethyltridecyl)-2H-1-benzopyran-6-ol; 2',3-bis[[3-[3,5-di-tert-butyl-4-hydroxyphenyl]propionyl]]propionohydrazide; isotridecyl-3-(3,5-di-tert-butyl-4-hydroxyphenyl) propionate; 2,2'-ethylidenebis(4,6-di-tert-butylphenol); ethylene bis[3,3-bis[3-(1,1-dimethylethyl)-4-hydroxyphenyl]butanoate]; 1,3,5-tris(4-tert-butyl-3-hydroxy-2,6-dimethylbenzyl)-1,3,5-triazine-2,4,6-(1H,3H,5H)-trione; 2,2'-methylenebis(4-methyl-6-tertbutylphenol); 3,5-bis(1,1-dimethylethyl)-4-hydroxy-benzenepropanoic acid, C13-15 alkyl esters; 2,2'-isobutylidenebis(2,4-dimethylphenol); 1,1,3-tris(2'-methyl-4'-hydroxy-5'-tert-butylphenyl)butane; Phosphite: bis-(2,4-di-t-butylphenol) pentaerythritol diphosphite; tris(2,4-di-tert-butylphenyl)phosphite; trinonylphenol phosphite; distearyl pentaerythritol diphosphite; trilauryl trithiophosphite; Thiosynergist: didodecyl-3,3'-thiodipropionate; dioctadecyl 3,3'-thiodipropionate; 2,2'-thiodiethylene bis[3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate]; 4,4'-thiobis(2-t-butyl-5-methylphenol); 2,2'-thiobis(6-tert-butyl-4-methylphenol); pentaerythritol tetrakis(b-laurylthiopropionate); Quencher: (2,2'-thiobis(4-tert-octyl-phenolato))-N-butylamine-nickel(II); Optical brightener: 2,2'-(2,5-thiophenediyl)bis(5-tert-butylbenzoxazole)	

HDPE high density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
BIODEGRADATION			
Typical biodegradants	-	fungi, bacteria, <i>Actinomyces</i> (3.5% mass loss per year)	Sudhakar, M; Doble, M; Sriyutha Murthy, P; Venkatesan, R, Int. Biodeg. Biodeg., 61, 203-13, 2008.
TOXICITY			
NFPA: Health, Flammability, Reactivity rating	-	0/1/0	
Carcinogenic effect	-	not listed by ACGIH, NIOSH, NTP	
TLV, ACGIH	mg m ⁻³	3 (respirable), 10 (total)	
OSHA	mg m ⁻³	5 (respirable), 15 (total)	
Oral rat, LD ₅₀	mg kg ⁻¹	>7,950	
Skin rabbit, LD ₅₀	mg kg ⁻¹	>2,000	
ENVIRONMENTAL IMPACT			
Aquatic toxicity, <i>Daphnia magna</i> , LC ₅₀ , 48 h	mg l ⁻¹	17,000-24,000	Lithner, Ph D Thesis, University of Gothenburg, 2011.
Cradle to grave non-renewable energy use	MJ/kg	72-76	Harding, K G; Dennis, J S; von Blottnitz, H; Harrison, S T L, J. Biotechnol., 130, 57-66, 2007.
Cradle to pellet greenhouse gasses	kg CO ₂ kg ⁻¹ resin	1.5-2.0	
PROCESSING			
Typical processing methods	-	blow molding, blown film extrusion, cast film extrusion, extrusion, extrusion coating, injection molding, rotational molding	
Preprocess drying: temperature/time/residual moisture	°C/h/%	60-80/2	
Processing temperature	°C	193-227 (extrusion)	
Additives used in final products	-	Fillers: aluminum, barium sulfate, calcium carbonate, calcium sulfate whiskers, carbon black, diatomaceous earth, ferromagnetic powder, glass fiber, glass spheres, ground tire rubber, hollow silicates, hydrotalcite, kaolin, lignin, magnesium hydroxide, marble, mica, nickel fibers, red mud, sand, silica, soot, starch, superconductor (YBa ₂ Cu ₃ O _{7-x}), talc, wollastonite, wood flour, zirconium silicate; Plasticizers: dioctyl phthalate, EPDM, EVA, glycerin, glyceryl tribenzoate, mineral oil, paraffin oil, polyethylene glycol, sunflower oil; Antistatics: carbon black, copper complex of polyacrylic acid, ethoxylated amines, fatty diethanol amines, glycerol monostearate, graphite, ionomer, lauric diethanolamide, polyethylene glycol, quaternary ammonium compound, trineoalkoxy zirconate; Anti-blocking: diatomaceous earth, natural silica, siloxane spheres, synthetic silica, talc, zeolite; Release: stearyl erucamide; Slip: erucamide, ethylene bisoleamide, oleamide	
Applications	-	freezer bags, industrial pipes, mining (slurry and leachate pipes), natural gas distribution pipes, oil and gas production, portable water pipes, wire and cable	
Outstanding properties	-	impact toughness processability; bimodal PE: high temperature/high pressure performance, resistance to rapid crack propagation, slow crack growth, toughness	

HDPE high density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
BLENDS			
Suitable polymers	-	EPDM, EVA, EVOH, LDPE, LLDPE, NR, PA6, PA12, PET, PMMA, PP, PS, PVC, SBS, SEBS, TPU, UHMWPE	
ANALYSIS			
FTIR (wavenumber-assignment)	cm ⁻¹ /-	C=O – 1715; CH ₂ – 1474, 1464, 730, 720; RCH=CH ₂ – 908	Stark, N M; Mantuana, L M, Polym. Deg. Stab., 86, 1-9, 2004.

LDPE low density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
GENERAL			
Common name	-	low density polyethylene	
IUPAC name	-	polyethylene	
Acronym	-	LDPE	
CAS number	-	9002-88-4 (homopolymer)	
Formula		$\left[\text{CH}_2\text{CH}_2 \right]_n$	
HISTORY			
Person to discover	-	Fawcett, E; Perrin, M, both of ICI	
Date	-	1933; 1935; 1939	
Details	-	Fawcett produced PE by accident; Perrin developed sound technology; ICI begun production	
SYNTHESIS			
Monomer(s) structure	-	$\text{H}_2\text{C}=\text{CH}_2$	Zhu, H; Wang, Y; Zhang, X; Su, Y; Dong, X; Chen, Q; Zhao, Y; Geng, C; Zhu, S; Han, C C; Wang, D, Polymer, 48, 5098-106, 2007.
Monomer(s) CAS number(s)	-	74-85-1	
Monomer(s) molecular weight(s)	dalton, g/mol, amu	28.05	
Monomer(s) expected purity(ies)	%	99.9	
Monomer ratio	-	100% ethylene or less	
Vinyl acetate content (only some grades)	wt%	3-6	
Formulation example	-	oxygen or an organic peroxide such as dibutyl, benzoyl, or diethyl peroxide used as initiator; benzene or chlorobenzene are used as solvents; tubular and autoclave reactors are used for synthesis	
Method of synthesis	-		
Temperature of polymerization	°C	132-332	
Time of polymerization	h	100-300	
Pressure of polymerization	MPa	150-300	
Number average molecular weight, M_n	dalton, g/mol, amu	13,000-18,000	
Mass average molecular weight, M_w	dalton, g/mol, amu	69,000-411,000	
Polydispersity, M_w/M_n	-	4-30	
Degree of branching	methyl/1000 C	7.8-33	
Type of branching	-	methyl, ethyl, butyl, amyl, and longer	
Unsaturations	% of total	80 (vinylidene), 10 (vinyl), 10 (trans)	
STRUCTURE			
Crystallinity	%	28.8-60	
Cell type (lattice)	-	orthorhombic	
Cell dimensions	nm	a:b:c=0.738:0.493:0.253	

LDPE low density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
Crystallite thickness	nm	6.5-10.5	Grady, B P; Genetti, W B, Conductive Polymers and Plastics, Rupprecht, L, Ed., WilliamAndrew, Norwich, 1999.
Rapid crystallization temperature	°C	96-100	
Avrami constants, k/n	-	n=1.5-3	
COMMERCIAL POLYMERS			
Some manufacturers	-	DOW; ExxonMobil	
Trade names	-	LDPE; LDPE	
PHYSICAL PROPERTIES			
Density at 20°C	g cm ⁻³	0.915-0.929; 0.855 (amorphous); 1.0-1.014 (crystalline)	
Refractive index, 20°C	-	1.517-1.526	
Transmittance	%	90-91	
Haze	%	2.2-27	
Gloss, 60°, Gardner (ASTM D523)	%	33-87	
Melting temperature, DSC	°C	105-115; 102 (copolymer with VAc)	
Thermal expansion coefficient, 23-80°C	°C ⁻¹	1-5.1E-4	
Thermal conductivity, melt	W m ⁻¹ K ⁻¹	0.55	
Glass transition temperature	°C	-103 to -133	
Heat of fusion	kJ mol ⁻¹	1.37-2.18	
Long term service temperature	°C	70	
Heat deflection temperature at 0.45 MPa	°C	37-48	
Heat deflection temperature at 1.8 MPa	°C	36-40	
Vicat temperature VST/A/50	°C	76-109	
Dielectric constant at 100 Hz/1 MHz	-	2.25-2.31	
Dissipation factor at 1000 Hz	E-4	2	
Volume resistivity	ohm-m	1E13	
Surface resistivity	ohm		
Electric strength K20/P50, d=0.60.8 mm	kV mm ⁻¹	16-28	
Arc resistance	s	135-160	
Power factor	-	0.0003	
Coefficient of friction	-	0.6 (itself, dynamic)	
Permeability to nitrogen, 25°C	cm ³ cm cm ⁻² s ⁻¹ Pa ⁻¹ x 10 ¹²	0.073	
Permeability to oxygen, 25°C	cm ³ cm cm ⁻² s ⁻¹ Pa ⁻¹ x 10 ¹²	0.22	

LDPE low density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
Permeability to water vapor, 25°C	cm ³ cm cm ² s ⁻¹ Pa ⁻¹ x 10 ¹²	6.8	
Diffusion coefficient of nitrogen	cm ² s ⁻¹ x10 ⁶	0.32	
Diffusion coefficient of oxygen	cm ² s ⁻¹ x10 ⁶	0.46	
Speed of sound	m s ⁻¹	32.5	
Acoustic impedance		1.79	
Attenuation	dB cm ⁻¹ , 5 MHz	2.4	

MECHANICAL & RHEOLOGICAL PROPERTIES

Tensile strength	MPa	10-20; 25.4-27.0 (MD) and 14.5-17.3 (TD) for 0.025 mm thick film; 21.6-31.8 (MD) and 16.9-28.9 (TD) for 0.051 mm thick film; 22.1-26.7 (copolymer with VAc)	
Tensile modulus	MPa	130-300	
Tensile stress at yield	MPa	10.8-14.1 (MD) and 10.0-12.3 (TD) for 0.025 mm thick film; 11.8-13.6 (MD) and 11.6-13.7 (TD) for 0.051 mm thick film	
Elongation	%	130-270 (MD) and 490-570 (TD) for 0.025 mm thick film; 180-580 (MD) and 560-780 (TD) for 0.051 mm thick film; 600 (copolymer VAc)	
Flexural modulus	MPa	230-250	
Izod impact strength, notched, 23°C	J m ⁻¹	420 to NB	
Film puncture resistance	J cm ⁻³	2.8-5.7	
Film toughness	J cm ⁻³	55.1-82.5 (MD) and 63.7-109 (TD) for 0.025 mm thick film; 64.5-216 (MD) and 66.9-211 (TD) for film thickness of 0.051 mm	
Dart drop impact	g	72-250; 120-1,200 (copolymer with VAc)	
Elmendorf tear strength	g	140-510 (MD) and 110-180 (TD) for 0.025 mm thick film; 300-560 (MD) and 180-470 (TD) for 0.051 mm thick film	
Puncture force	N	37	
Shore D hardness	-	41-50	
Shrinkage	%	2.4	
Brittleness temperature (ASTM D746)	°C	-34 to -60	
Melt viscosity, shear rate=0 s ⁻¹ at 150°C	Pa s	54,500	Hertel, D; Valette, R; Muenstedt, H, J. Non-Newtonian Fluid Mech., 153, 82-94, 2008.
Pressure coefficient of melt viscosity, b	G Pa ⁻¹	17.6	Aho, J; Syrjala, S, J. Appl. Polym. Sci., 117, 1076-84, 2010.
Melt index, 230°C/3.8 kg	g/10 min	0.25-55	
Water absorption, equilibrium in water at 23°C	%	0.005-0.015	

CHEMICAL RESISTANCE

Acid dilute/concentrated	-	very good	
Alcohols	-	good	

LDPE low density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
Alkalis	-	very good	
Aliphatic hydrocarbons	-	poor	
Aromatic hydrocarbons	-	poor	
Esters	-	poor	
Greases & oils	-	good to poor	
Halogenated hydrocarbons	-	poor	
Ketones	-	poor	
⊙ solvent, ⊖-temp.=141-170	-	di-(2-ethylhexyl) adipate	
Good solvent	-	1,2,4-trichlorobenzene, decalin, halogenated hydrocarbons, aliphatic ketones, xylene (all above 80°C)	
Non-solvent	-	most common solvents	
FLAMMABILITY			
Ignition temperature	°C	340-343	Lyon, R E; Walters, R N, J. Anal. Appl. Pyrolysis, 71, 27-46, 2004.
Autoignition temperature	°C	350	
Limiting oxygen index	% O ₂	<20	
Char at 500°C	%	0	
Heat of combustion	J g ⁻¹	47,740	
Volatile products of combustion	-	CO, CO ₂ , aldehydes, benzene	
UL rating	-	HB	
WEATHER STABILITY			
Spectral sensitivity	nm	<300	
Activation wavelengths	nm	300, 330-360	
Excitation wavelengths	nm	230, 254, 265, 273, 278, 280, 300, 331	
Emission wavelengths	nm	275, 295, 335, 350, 378, 381, 391, 405, 416, 420, 435, 455, 470	
Depth of UV penetration	μm	<1500	
Important initiators and accelerators	-	unsaturations, aromatic carbonyl compounds (deoxyanisoin, dibenzocycloheptadienone, flavone, 4-methoxybenzophenone, 10-thioxanthone), hydrogen bound to tertiary carbon at branching points, aromatic amines, groups formed on oxidation (hydroperoxides, carbonyl, carboxyl, hydroxyl) substituted benzophenones, complexes with ground-state oxygen, quinones (anthraquinone, 2-chloroanthraquinone, 2-tert-butylathraquinone, 1-methoxyanthraquinone, 2-ethylanthraquinone, 2-methylantraquinone), transition metal compounds (Ni < Zn < Fe < Co), ferrocene derivatives, titanium dioxide (anatase), ferric stearate, polynuclear aromatic compounds (anthracene, phenanthrene, pyrene, naphthalene)	
Products of degradation	-	free radicals, hydroperoxides, carbonyl groups, chain scission, crosslinking	

LDPE low density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
Stabilizers	-	UVA: 2-hydroxy-4-octyloxybenzophenone; phenol, 2-(5-chloro-2H-benzotriazole-2-yl)-6-(1,1-dimethylethyl)-4-methyl-; 2,2'-methylenebis(6-(2H-benzotriazol-2-yl)-4-1,1,3,3-tetramethylbutyl)phenol; 2,4-di-tert-butyl-6-(5-chloro-2H-benzotriazole-2-yl)-phenol; reaction product of methyl 3(3-(2H-benzotriazole-2-yl)-5-t-butyl-4-hydroxyphenyl propionate/PEG 300; 2-[4,6-bis(2,4-dimethylphenyl)-1,3,5-triazin-2-yl]-5-(octyloxy) phenol; Screener: titanium dioxide; zinc oxide; carbon black; Acid scavenger: hydrotalcite; Fiber: carbon nanotube; 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-piperidiny)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-piperidiny)]-; bis(1,2,2,6,6-pentamethyl-4-piperidyl)sebacate + methyl-1,2,2,6,6-pentamethyl-4-piperidyl sebacate; 2,2,6,6-tetramethyl-4-piperidiny stearate; reaction products of N,N'-ethane-1,2-diylbis(1,3-propanediamine), cyclohexane, peroxidized 4-butylamino-2,2,6,6-tetramethylpiperidine and trichloro-1,3,5-triazine; poly[[[6-(1,1,3,3-tetramethylbutyl) amino]-1,3,5-triazine-2,4-diyl][2,2,6,6-tetramethyl-4-piperidiny] imino]-1,6-hexanediyl[2,2,6,6-tetramethyl-4-piperidiny]imino]; 1,6-hexanediamine- N,N'-bis(2,2,6,6-tetramethyl-4-piperidiny)-polymer with 2,4,6-trichloro-1,3,5-triazine, reaction products with N-butyl-1-butanamine an N-butyl-2,2,6,6-tetramethyl-4-piperidinamine; butanedioic acid, dimethylester, polymer with 4-hydroxy-2,2,6,6-tetramethyl-1-piperidine ethanol; 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-piperidiny)-, polymers with morpholine-2,4,6-trichloro-1,3,5-triazine reaction products, methylated; Phenolic antioxidant: 2,6-di-tert-butyl-4-(4,6-bis(octylthio)-1,3,5,-triazine-2-ylamino) phenol; pentaerythritol tetrakis(3-(3,5-di-tert-butyl-4-hydroxyphenyl) propionate); octadecyl-3-(3,5-di-tert-butyl-4-hydroxyphenyl)-propionate; 3,3',3',5',5',5'-hexa-tert-butyl-a,a',a'- (mesitylene-2,4,6-triyl)tri-p-cresol; 2-(1,1-dimethylethyl)-6-[[3-(1,1-dimethylethyl)-2-hydroxy-5-methylphenyl] methyl-4-methylphenyl acrylate; 1,3,5-tris(3,5-di-tert-butyl-4-hydroxybenzyl)-1,3,5-triazine-2,4,6-(1H,3H,5H)-trione; 3,4-dihydro-2,5,7,8-tetramethyl-2-(4,8,12-trimethyltridecyl)-2H-1-benzopyran-6-ol; 2',3-bis[[3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionyl]]propionohydrazide; isotridecyl-3-(3,5-di-tert-butyl-4-hydroxyphenyl) propionate; 2,2'-ethylidenebis (4,6-di-tert-butylphenol); ethylene bis[3,3-bis[3-(1,1-dimethylethyl)-4-hydroxyphenyl]butanoate]; 1,3,5-tris(4-tert-butyl-3-hydroxy-2,6-dimethylbenzyl)-1,3,5-triazine-2,4,6-(1H,3H,5H)-trione; 2,2'-methylenebis(4-methyl-6-tertbutylphenol); 3,5-bis(1,1-dimethylethyl)-4-hydroxy-benzenepropanoic acid, C13-15 alkyl esters; 2,2'-isobutylidenebis(2,4-dimethylphenol); 1,1,3-tris(2'methyl-4'-hydroxy-5'tert-butylphenyl)butane; Phosphite: bis-(2,4-di-t-butylphenol) pentaerythritol diphosphite; tris (2,4-di-tert-butylphenyl)phosphite; trinonylphenol phosphite; distearyl pentaerythritol diphosphite; triauryl trithiophosphite; Thiosynergist: didodecyl-3,3'-thiodipropionate; dioctadecyl 3,3'-thiodipropionate; 2,2'-thiodiethylene bis[3-(3,5-ditert-butyl-4-hydroxyphenyl)propionate]; 4,4'-thiobis(2-t-butyl-5-methylphenol); 2,2'-thiobis(6-tert-butyl-4-methylphenol); pentaerythritol tetrakis(b-laurylthiopropionate); Quencher: (2,2'-thiobis(4-tert-octyl-phenolato))-N-butylamine-nickel(II); Optical brightener: 2,2'-(2,5-thiophenediyl)bis(5-tert-butylbenzoxazole)	

LDPE low density polyethylene

PROPERTY	UNIT	VALUE	REFERENCES
BIODEGRADATION			
Typical biodegradants	-	fungi, bacteria, <i>Actinomyces</i> (10% mass loss per year)	Sudhakar, M; Doble, M; Sriyutha Murthy, P; Venkatesan, R, Int. Biodeg., 61, 203-13, 2008.
TOXICITY			
NFPA: Health, Flammability, Reactivity rating	-	1/0/1	
Carcinogenic effect	-	not listed by ACGIH, NIOSH, NTP	
Mutagenic effect	-	not known	
Teratogenic effect	-	not known	
Reproductive toxicity	-	not known	
Oral rat, LD ₅₀	mg kg ⁻¹	>5,000	
Skin rabbit, LD ₅₀	mg kg ⁻¹	>2,000	
ENVIRONMENTAL IMPACT			
Biological oxygen demand, BOD ₅	-	3.08	Psomiadou, E; Arvanitoyannis, I; Biliaderis, C G; Ogawa, H; Kawasaki, N, Carbohydrate Polym., 33, 227-42, 1997.
Cradle to grave non-renewable energy use	MJ/kg	81.8	Harding, K G; Dennis, J S; von Blottnitz, H; Harrison, S T L, J. Biotechnol., 130, 67-66, 2007.
Cradle to pellet greenhouse gasses	kg CO ₂ kg ⁻¹ resin	2.0-2.2	
PROCESSING			
Typical processing methods	-	blown film extrusion, cast film extrusion, coating, coextrusion, extrusion, injection molding, molding, lamination, rotational molding	
Processing temperature	°C	199-232 (extrusion); 212 (blown film); 316-332 (coating)	
Additives used in final products	-	Fillers: aluminum, barium sulfate, calcium carbonate, calcium sulfate whiskers, carbon black, diatomaceous earth, ferromagnetic powder, glass fiber, glass spheres, ground tire rubber, hollow silicates, hydrotalcite, kaolin, lignin, magnesium hydroxide, marble, mica, nickel fibers, red mud, sand, silica, soot, starch, superconductor (YBa ₂ Cu ₃ O _{7-x}), talc, wollastonite, wood flour, zirconium silicate; Plasticizers: dioctyl phthalate, EPDM, EVA, glycerin, glyceryl tribenzoate, mineral oil, paraffin oil, polyethylene glycol, sunflower oil; Antistatics: carbon black, copper complex of polyacrylic acid, ethoxylated amines, fatty diethanol amines, glycerol monostearate, graphite, ionomer, lauric diethanolamide, polyethylene glycol, quaternary ammonium compound, trineoalkoxy zirconate; Antiblocking: diatomaceous earth, natural silica, siloxane spheres, synthetic silica, talc, zeolite; Release: stearyl erucamide; Slip: erucamide, ethylene bisoleamide, oleamide	
Applications	-	car covers, cling wrap, moisture barriers in construction, liners for tanks and ponds, sandwich bags, squeeze bottles	
BLENDS			
Suitable polymers	-	EPDM, EVA, HDPE, HIPS, LLDPE, NBR, NR, PA6, PET, IPP, PP, PS, PVDF, SBR, starch	

LLDPE linear low density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
GENERAL			
Common name	-	linear low density polyethylene; poly(ethylene-co-1-octene); poly(ethylene-co-1-butene); poly(ethylene-co-1-hexene)	
IUPAC name	-	polyethylene	
Acronym	-	LLDPE	
CAS number	-	26221-73-8 (octene); 25087-34-7 (butene); 25213-02-9 (hexene); metallocene	
SYNTHESIS			
Monomer(s) structure	-	$H_2C=CH_2$; $CH_3CH_2CH=CH_2$; $CH_3(CH_2)_3CH=CH_2$	
Monomer(s) CAS number(s)	-	74-85-1; 106-98-9; 592-41-6	
Monomer(s) molecular weight(s)	dalton, g/mol, amu	28.05; 56.11; 84.16	
Monomer(s) expected purity(ies)	%	99.9	
Method of synthesis	-	Ziegler or Phillips catalysts are used in solution or gas phase reactions to obtain LLDPE. Octene copolymer with ethylene is obtained in solution process and butene and hexene are copolymerized with ethylene in gas phase reactors; also metallocene catalyst are in use	
Catalyst	-	Ziegler, Phillips, metallocene	
Typical additives	ppm	3,000 (antiblock), antioxidant (e.g., Tufin)	
Mass average molecular weight, M_w	dalton, g/mol, amu	94,000-208,000	
Polydispersity, M_w/M_n	-	1.6-35	
Degree of branching	mol%	2-4	
STRUCTURE			
Crystallinity	%	30-53; 46 (DSC); 52-59 (NMR)	Lu, J; Zhao, B; Sue, H-J, Metallocene Technology in Commercial Applications, Benedikt, G M, Ed., William Andrew, Norwich, 1999.
Cell type (lattice)	-	orthorhombic	
Cell dimensions	nm	a:b:c=0.748:0.497:0.257	
Spherulite size	nm	2,000-12,000	Ruksakulpiwat, Y, Antec, 582-6, 2001.
Spacing between crystallites	nm	8.0-36.9	
Lamellae thickness	nm	4.3-16.3	
Rapid crystallization temperature	°C	107-123 (injection molding grades)	
COMMERCIAL POLYMERS			
Some manufacturers	-	DOW; ExxonMobil; LyondellBasell	
Trade names	-	Aspun (fiber grades), Dowlex, Tufin, LLDPE; LLDPE; Starflex	
PHYSICAL PROPERTIES			
Density at 20°C	g cm ⁻³	0.905-0.942	
Bulk density at 20°C	g cm ⁻³	0.35-0.38	
Color	-	clear to white	
Refractive index, 20°C	-	1.49-1.52	

LLDPE linear low density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
Haze	%	1-19	
Gloss, 60°, Gardner (ASTM D523)	%	47-92	
Odor		odorless to mild hydrocarbon odor	
Melting temperature, DSC	°C	120-136; 94 (injection molding grades)	
Thermal expansion coefficient, 23-80°C	°C ⁻¹	1.6-5E-4	
Thermal conductivity, melt	W m ⁻¹ K ⁻¹	0.55	
Glass transition temperature	°C	-110	
Heat of fusion	kJ mol ⁻¹	1.37-2.18	
Maximum processing temperature	°C	300 (Booster)	
Heat deflection temperature at 0.45 MPa	°C	43-59	
Heat deflection temperature at 1.8 MPa	°C	38	
Vicat temperature VST/A/50	°C	94-123	
Surface tension	mN m ⁻¹	22.4-24.0	Tinson, A; Takacs, E; Vlachopoulos, J, Antec, 870-74, 2004.
Dielectric constant at 100 Hz/1 MHz	-	2.3	
Coefficient of friction	-	0.6 (itself, dynamic)	
Contact angle of water, 20°C	degree	99.1	
Speed of sound	m s ⁻¹	717-1009	

MECHANICAL & RHEOLOGICAL PROPERTIES

Tensile strength	MPa	25-45; 33-71 (MD) and 25-54.2 (TD) for 0.02-0.25 mm thick film; 30-55 (MD) and 29-53.6 (TD) for 0.051 mm thick film; 7.6-15.5 (injection molding grades)	
Tensile modulus	MPa	260-520	
Tensile stress at yield	MPa	8.1-32.4 (MD) and 7.7-29.0 (TD) for 0.02-0.025 mm thick film; 9.3-15.2 (MD) and 10.0-16.4 (TD) for 0.051 mm thick film; 11-750-830 (film grade); 16.5 (injection molding grades)	
Elongation	%	300-830 (MD); 610-890 (TD); 50-800 (injection molding grades)	
Tensile yield strain	%	2-18	
Flexural modulus	MPa	280-735; 310-700 (injection molding grades)	
Izod impact strength, notched, 23°C	J m ⁻¹	54 to NB	
Dart drop impact (film thickness in mm)	g	43-470 (0.02); 130-610 (0.051)	
Film puncture resistance (film thickness in mm)	J cm ⁻³	7.7-30.8 (0.02); 7.0-24.0 (0.051)	
Toughness	J cm ⁻³	63-303 (MD) and 76-353 (TD) for 0.02-0.025 mm thick film; 84-346 (MD) and 87-361 (TD) for 0.051 mm thick film	
Elmendorf tear strength (film thickness in mm)	g	15-370 (MD) and 210-700 (TD) for 0.02-0.025 mm thick film; 470-950 (MD) and 1,100-1,300 (TD) for 0.051 mm thick film	
Puncture force	N	30-43	
Shore D hardness	-	55-56; 44-53 (injection molding grades)	

LLDPE linear low density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
Shrinkage	%	2.0-2.5	Tinson, A; Takacs, E; Vlachopoulos, J, Antec, 870-74, 2004; Hertel, D; Valette, R; Muenstedt, H, J. Non-Newtonian Fluid Mech., 153, 82-94, 2008.
Brittleness temperature (ASTM D746)	°C	-20 to -100 (injection molding grades)	
Melt viscosity, shear rate=0 s ⁻¹	kPa s	2.9 (190°C); 25.5 (150°C)	
Melt index	g/10 min	0.2-160	
Water absorption	%	0.005-0.01	
CHEMICAL RESISTANCE			
Acid dilute/concentrated	-	very good	
Alcohols	-	good	
Alkalis	-	very good	
Aliphatic hydrocarbons	-	poor	
Aromatic hydrocarbons	-	poor	
Esters	-	poor	
Greases & oils	-	good to poor	
Halogenated hydrocarbons	-	poor	
Ketones	-	poor	
Good solvent	-	cyclohexene, decalin, toluene, xylene	
Non-solvent	-	o-dichlorobenzene, 1,2-dichloropropane, methylene chloride	
FLAMMABILITY			
Ignition temperature	°C	340-343	
Autoignition temperature	°C	350	
Limiting oxygen index	% O ₂	<20	
Heat of combustion	J g ⁻¹	47,740	
Volatile products of combustion	-	CO, CO ₂ , aldehydes, benzene	
UL rating	-	HB	
WEATHER STABILITY			
Spectral sensitivity	nm	<300	
Activation wavelengths	nm	300, 330-360	
Excitation wavelengths	nm	230, 265, 275, 290, 292	
Emission wavelengths	nm	295, 312, 330, 344, 358, 450	
Important initiators and accelerators	-	unsaturations, aromatic carbonyl compounds (deoxyanisoin, dibenzocycloheptadienone, flavone, 4-methoxybenzophenone, 10-thioxanthone), hydrogen bound to tertiary carbon at branching points, aromatic amines, groups formed on oxidation (hydroperoxides, carbonyl, carboxyl, hydroxyl) substituted benzophenones, complexes with ground-state oxygen, quinones (anthraquinone, 2-chloroanthraquinone, 2-tert-butylanthraquinone, 1-methoxyanthraquinone, 2-ethylanthraquinone, 2-methylanthraquinone), transition metal compounds (Ni < Zn < Fe < Co), ferrocene derivatives, titanium dioxide (anatase), ferric stearate, polynuclear aromatic compounds (anthracene, phenanthrene, pyrene, naphthalene)	

LLDPE linear low density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
Products of degradation	-	free radicals, hydroperoxides, carbonyl groups, chain scission, crosslinking	
Stabilizers	-	UVA: 2-hydroxy-4-octyloxybenzophenone; phenol, 2-(5-chloro-2H-benzotriazole-2-yl)-6-(1,1-dimethylethyl)-4-methyl-; 2,2'-methylenebis(6-(2H-benzotriazole-2-yl)-4-1,1,3,3-tetramethylbutyl)phenol; 2,4-di-tert-butyl-6-(5-chloro-2H-benzotriazole-2-yl)-phenol; reaction product of methyl 3(3-(2H-benzotriazole-2-yl)-5-tert-butyl-4-hydroxyphenyl propionate/PEG 300; 2-[4,6-bis(2,4-dimethylphenyl)-1,3,5-triazin-2-yl]-5-(octyloxy) phenol; Screener: titanium dioxide; zinc oxide; carbon black; Acid scavenger: hydrotalcite; Fiber: carbon nanotube; 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-piperidyl)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-piperidyl)-bis(1,2,2,6,6-pentamethyl-4-piperidyl)sebacate + methyl-1,2,2,6,6-pentamethyl-4-piperidyl sebacate; 2,2,6,6-tetramethyl-4-piperidyl stearate; reaction products of N,N'-ethane-1,2-diylbis(1,3-propanediamine), cyclohexane, peroxidized 4-butylamino-2,2,6,6-tetramethylpiperidine and trichloro-1,3,5-triazine; poly[[[6-(1,1,3,3-tetramethylbutyl) amino]-1,3,5-triazine-2,4-diyl][2,2,6,6-tetramethyl-4-piperidyl] imino]-1,6-hexanediyl[2,2,6,6-tetramethyl-4-piperidyl]imino]; 1,6-hexanediamine- N,N'-bis(2,2,6,6-tetramethyl-4-piperidyl)-polymer with 2,4,6-trichloro-1,3,5-triazine, reaction products with N-butyl-1-butanamine an N-butyl-2,2,6,6-tetramethyl-4-piperidinamine; butanedioic acid, dimethylester, polymer with 4-hydroxy-2,2,6,6-tetramethyl-1-piperidine ethanol; 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-piperidyl)-, polymers with morpholine-2,4,6-trichloro-1,3,5-triazine reaction products, methylated; Phenolic antioxidant: 2,6-di-tert-butyl-4-(4,6-bis(octylthio)-1,3,5-triazine-2-ylamino) phenol; pentaerythritol tetrakis(3-(3,5-di-tert-butyl-4-hydroxyphenyl) propionate); octadecyl-3-(3,5-di-tert-butyl-4-hydroxyphenyl)-propionate; 3,3',3',5,5',5'-hexa-tert-butyl-a,a',a'-(mesitylene-2,4,6-triyl)tri-p-cresol; 2-(1,1-dimethylethyl)-6-[[3-(1,1-dimethylethyl)-2-hydroxy-5-methylphenyl] methyl-4-methylphenyl acrylate; 1,3,5-tris(3,5-di-tert-butyl-4-hydroxybenzyl)-1,3,5-triazine-2,4,6-(1H,3H,5H)-trione; 3,4-dihydro-2,5,7,8-tetramethyl-2-(4,8,12-trimethyltridecyl)-2H-1-benzopyran-6-ol; 2',3-bis[[3-[3,5-di-tert-butyl-4-hydroxyphenyl]propionyl]]propionohydrazide; isotridecyl-3-(3,5-di-tert-butyl-4-hydroxyphenyl) propionate; 2,2'-ethylidenebis(4,6-di-tert-butylphenol); ethylene bis[3,3-bis[3-(1,1-dimethylethyl)-4-hydroxyphenyl]butanoate]; 1,3,5-tris(4-tert-butyl-3-hydroxy-2,6-dimethylbenzyl)-1,3,5-triazine-2,4,6-(1H,3H,5H)-trione; 2,2'-methylenebis(4-methyl-6-tert-butylphenol); 3,5-bis(1,1-dimethylethyl)-4-hydroxy-benzenepropanoic acid, C13-15 alkyl esters; 2,2'-isobutylidenebis(2,4-dimethylphenol); 1,1,3-tris(2'-methyl-4'-hydroxy-5'-tert-butylphenyl)butane; Phosphite: bis-(2,4-di-tert-butylphenol) pentaerythritol diphosphite; tris (2,4-di-tert-butylphenyl)phosphite; trinonylphenol phosphite; distearyl pentaerythritol diphosphite; triauryl trithiophosphite; Thiosynergist: didodecyl-3,3'-thiodipropionate; dioctadecyl 3,3'-thiodipropionate; 2,2'-thiodiethylene bis[3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate]; 4,4'-thiobis(2-tert-butyl-5-methylphenol); 2,2'-thiobis(6-tert-butyl-4-methylphenol); pentaerythritol tetrakis(b-laurylthiopropionate); Quencher: (2,2'-thiobis(4-tert-octyl-phenolato))-N-butylamine-nickel(II); Optical brightener: 2,2'-(2,5-thiophenediyl)bis(5-tert-butylbenzoxazole)	

LLDPE linear low density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
BIODEGRADATION			
Typical biodegradants	-	<i>Bacillus</i>	Abrusci, C; Pablos, J L; Corrales, T; Lopez-Marin, J; Marin, I; Catalina, F, Int. Biodet. Biodeg., 65, 461-59, 2011.
TOXICITY			
NFPA: Health, Flammability, Reactivity rating	-	0/1/0	
Carcinogenic effect	-	not listed by ACGIH, NIOSH, NTP	
Mutagenic effect	-	not known	
Teratogenic effect	-	not known	
Reproductive toxicity	-	not known	
Oral rat, LD ₅₀	mg kg ⁻¹	>5,000	
Skin rabbit, LD ₅₀	mg kg ⁻¹	>2,000	
ENVIRONMENTAL IMPACT			
Cradle to grave non-renewable energy use	MJ/kg	69-73	
Cradle to pellet greenhouse gasses	kg CO ₂ kg ⁻¹ resin	1.8-2.0	
PROCESSING			
Typical processing methods	-	blown film, blow molding, coating, extrusion, injection molding, slot cast extrusion	
Processing temperature	°C	180-327; 180-220 (extrusion of blown film); 200-240 (injection)	
Processing pressure	MPa	20-60 (holding)	
Additives used in final products	-	Antistatics: carbon black, copper complex of polyacrylic acid, ethoxylated amines, fatty diethanol amines, glycerol monostearate, graphite, ionomer, lauric diethanolamide, polyethylene glycol, quaternary ammonium compound, trineoalkoxy zirconate; Antiblocking: diatomaceous earth, natural silica, siloxane spheres, synthetic silica, talc, zeolite; Blowing agents; Release: stearyl erucamide; Slip: erucamide, ethylene bisoleamide, oleamide; Process aid; Thermal stabilizers; UV stabilizers	
Applications	-	automotive parts, agricultural film, bags, bottles, cast film, cling film, closures, diaper backsheet, drum liners, film, greenhouse film, hoses, lids, melt strength enhancer (Booster); overwrap film, parts of industrial containers, playground equipment, point of display cabinets, potable water tanks, toys, trash cans, tubing	
Outstanding properties	-	tear strength, toughness, processability, stiffness	

LLDPE linear low density polyethylene

PARAMETER	UNIT	VALUE	REFERENCES
BLENDS			
Suitable polymers	-	EPDM, EVA, LDPE, NR, PA6, PC, PMMA, PP, PVC, SBS, starch	