

Content

Preface	V
1 Introduction	1
1.1 Historic Note	1
1.2 Role of Plastics in Packaging	3
1.3 Book Structure	7
1.4 References	8
2 Basic Concepts and Definitions	9
2.1 Terminology	9
2.1.1 Macromolecule	9
2.1.2 Polymer	10
2.1.3 Plastic	12
2.1.4 Monomer	12
2.1.5 Constitutional Unit	13
2.1.6 Homopolymer	13
2.1.7 Copolymer	13
2.2 Polymer Nomenclature	14
2.3 Interatomic and Intermolecular Forces in Polymers	16
2.3.1 Interatomic Forces	16
2.3.1.1 Covalent Bonds	16
2.3.1.2 Ionic Bonds	17
2.3.2 Intermolecular and Intramolecular Forces	18
2.3.2.1 Dispersion Forces	19
2.3.2.2 Induction Forces	19
2.3.2.3 Dipole Forces	19
2.3.2.4 Hydrogen Bonds	20
2.4 Properties Determined by Chemical Composition	20
2.5 Categorization of Plastics	21

2.6	References	22
	Study Questions	22
3	Polymer Structure and Properties	25
3.1	Introduction	25
3.2	Molecular Architecture	25
3.2.1	Linear Polymers	26
3.2.2	Branched Polymers	26
3.2.3	Cross-Linked Polymers	28
3.3	Copolymer Structure	29
3.3.1	Random Copolymers	29
3.3.2	Alternating Copolymers	30
3.3.3	Block Copolymers	30
3.3.4	Graft Copolymers	32
3.3.5	Combinations of Copolymer Types	33
3.4	Chain Polymerization, Addition Polymers	33
3.4.1	Addition or Chain Polymerization Mechanism	34
3.4.2	Vinyl Polymers	35
3.4.3	Free-Radical Polymerization	37
3.4.3.1	Initiation	37
3.4.3.2	Propagation	37
3.4.3.3	Termination	38
3.4.4	Polyethylene Polymerization Processes	38
3.4.5	Other Addition Polymerization Mechanisms	42
3.5	Molecular Configuration and Conformation	42
3.6	Head-to-Head and Head-to-Tail	43
3.6.1	Configurations of Vinyl Polymers	43
3.7	Stereochemistry	44
3.8	Step Polymerization, Condensation Polymers	47
3.9	Molecular Weight and Molecular Weight Distribution	51
3.9.1	Degree of Polymerization	51
3.9.2	Molecular Mass (Weight) and Molecular Weight Distribution	52
3.9.3	Number Average Molecular Weight	53
3.9.4	Weight Average Molecular Weight	53
3.9.5	Other Molecular Weight Averages	56
3.9.6	Determination of MWD	57
3.9.7	Effect of Molecular Weight and Molecular Weight Distribution on Flow and Mechanical Properties	57
3.10	Polymer Morphology	61
3.10.1	Crystallinity	61

3.10.2	Polymer Orientation	67
3.10.3	Degree of Crystallinity	69
3.11	Thermal Properties	71
3.11.1	Melting Temperature	71
3.11.2	Glass Transition Temperature	71
3.11.2.1	Measuring T_g	75
3.11.2.2	Variables Affecting T_g	75
3.11.3	Other Thermal Transitions	77
3.11.4	Heat Capacity	78
3.11.5	Heat of Fusion	78
3.11.6	Thermal Conductivity	79
3.11.7	Thermal Expansion Coefficient	79
3.11.8	Other Dimensional Changes	80
3.11.9	Dimensional Stability	81
3.12	Mechanical Properties	81
3.12.1	Tensile Properties	81
3.12.2	Tear Strength	90
3.12.3	Impact and Bursting Strength	90
3.12.4	Other Mechanical Properties	91
3.13	Barrier Properties	92
3.13.1	Diffusion Coefficient	92
3.13.2	Solubility Coefficient	93
3.13.3	Permeability Coefficient	93
3.14	Surfaces and Adhesion	93
3.14.1	Surface Tension	93
3.14.2	Wettability	94
3.14.3	Adhesive Bond Strength	94
3.14.4	Cohesive Bond Strength	94
3.14.5	Blocking	95
3.14.6	Friction	95
3.14.7	Heat Sealing	96
3.15	Optical Characteristics	96
3.15.1	Gloss	97
3.15.2	Haze	97
3.15.3	Transparency and Opacity	98
3.16	Electrical Properties	98
3.17	Plastics Identification Using IR Spectrophotometry	99
3.18	References	101
	Study Questions	101

4	Major Plastics in Packaging	105
4.1	Branched Polyethylenes	105
4.1.1	Low Density Polyethylene	106
4.1.2	Ethylene Vinyl Acetate (EVA)	108
4.1.3	Ethylene Acrylic Acid (EAA)	109
4.1.4	Ionomers	110
4.2	Linear Polyethylenes	111
4.2.1	High Density Polyethylene (HDPE)	112
4.2.2	Linear Low Density Polyethylene (LLDPE)	114
4.2.3	Metallocene Polymers	115
4.2.4	Property Trends in the Polyethylene Family	120
4.3	Polypropylene (PP)	121
4.3.1	PP Homopolymer	121
4.3.2	Random Copolymer Polypropylene	123
4.4	Polyvinyl Chloride (PVC)	124
4.5	Vinylidene Chloride Copolymers (PVDC)	126
4.6	Polystyrene (PS)	128
4.7	Polyvinyl Alcohol (PVOH) and Ethylene Vinyl Alcohol (EVOH)	130
4.7.1	Polyvinyl Alcohol	130
4.7.2	Ethylene Vinyl Alcohol	131
4.8	Nylon	133
4.9	Polyester	135
4.9.1	Polyethylene Terephthalate (PET)	136
4.9.2	Glycol Modified PET, Other PET Copolymers, and PET Blends	138
4.9.3	Polyethylene Naphthalate (PEN)	138
4.10	Polycarbonate (PC)	139
4.11	Fluoropolymers	141
4.12	Styrene-Butadiene Copolymers	142
4.13	Acrylonitrile Copolymers	142
4.14	Cyclic Olefin Copolymers	143
4.15	Liquid Crystal Polymers	144
4.16	Conductive Polymers	145
4.17	Thermoplastic Elastomers	146
4.18	Biobased Plastics	146
4.18.1	Cellophane	147
4.18.2	Cellulosic Plastics	149
4.18.3	Starch-Based Plastics	150
4.18.4	Poly(Lactic Acid) - PLA	151

4.18.5	Polyhydroxyalkanoates	153
4.18.6	Biobased Polyolefins	154
4.18.7	Biobased PET	155
4.18.8	Other Biobased Plastics	155
4.19	Thermosets	157
4.20	Polymer Blends	159
4.21	Comparison Chart of Major Plastics	161
4.22	References	162
	Study Questions	163
5	Additives and Compounding	165
5.1	Introduction	165
5.2	Compounding	166
5.3	Antioxidants	166
5.4	Heat Stabilizers	171
5.5	UV Stabilizers	172
5.6	Additives to Modify Surface Attractions	174
5.6.1	Antiblocking Agents	174
5.6.2	Slip Agents	175
5.6.3	Antislip Agents	175
5.6.4	Lubricants	176
5.6.5	Mold Release Agents	176
5.7	Colorants	176
5.7.1	Dyes	177
5.7.2	Organic Pigments	177
5.7.3	Inorganic Pigments	178
5.7.4	Specialty Pigments	179
5.7.5	Colorants and the FDA	179
5.8	Antifogging Agents	180
5.9	Nucleating Agents	180
5.10	Antistatic Agents	181
5.11	Plasticizers	183
5.12	Oxygen Scavengers, Desiccants, and Fragrance Enhancers	184
5.13	Fillers and Reinforcements	187
5.14	Antimicrobials or Biocides	187
5.15	Nanoclays and Related Additives	188
5.16	Other Additives	189
	Study Questions	189

6	Adhesion, Adhesives, and Heat Sealing	191
6.1	Adhesion	191
6.2	Adhesives	192
6.3	Adhesive and Cohesive Bond Strength	193
6.3.1	Adhesive Bond Strength	194
6.3.1.1	Surface Tension	194
6.3.1.2	Solubility Parameter	195
6.3.1.3	Viscosity	198
6.3.1.4	Estimation of Adhesive Bond Strength	198
6.3.2	Cohesive Bond Strength	199
6.4	Types of Adhesives	200
6.4.1	Reactive Adhesives	200
6.4.2	Hot Melt Adhesives	201
6.4.3	Solvent-Borne Adhesives	201
6.4.4	Water-Borne Adhesives	202
6.4.5	Pressure Sensitive and Remoistenable Adhesives	203
6.4.6	Cold-Seal Adhesives	204
6.4.7	UV- and E-Beam Curing	204
6.5	Application of Adhesives	204
6.6	Adhesive Terminology	206
6.7	Adhesive Additives	207
6.8	Heat Sealing	208
6.8.1	Sealing Methods	209
6.8.1.1	Bar or Thermal Sealing	209
6.8.1.2	Impulse Sealing	210
6.8.1.3	Band Sealing	210
6.8.1.4	Hot Wire or Hot Knife Sealing	211
6.8.1.5	Ultrasonic Sealing	211
6.8.1.6	Friction Sealing	211
6.8.1.7	Hot Gas Sealing and Contact Sealing	212
6.8.1.8	Radiant Sealing	212
6.8.1.9	Dielectric Sealing	212
6.8.1.10	Magnetic Sealing	212
6.8.1.11	Induction Sealing	213
6.8.1.12	Solvent Sealing	213
6.8.2	Heat Conduction in Multilayer Flexible Materials	214
6.8.3	Hot Tack	215
6.8.4	Heat-Seal Jaws	215
6.8.5	Heat-Seal Failure Modes	216
6.8.6	Evaluation of Seals in Flexible Packaging Materials	217

6.9	References	218
	Study Questions	218
7	Extrusion, Film and Sheet	219
7.1	Extrusion and Extruders	219
7.1.1	Hopper and Feed Port	220
7.1.2	Feed Section	221
7.1.3	Compression Section	222
7.1.4	Metering Section	223
7.1.5	Mixing Devices	223
7.1.6	Extruder, Screw Design and Size	224
7.1.7	Dies	225
7.1.8	Melt Filters	225
7.1.9	Drive Mechanisms and Screw Speeds	225
7.1.10	Special Designs	226
7.1.11	Extrusion Temperatures	226
7.1.12	Extrusion Pressures	228
7.1.13	Specific Mechanical Energy	228
7.2	Cast Film and Sheet	229
7.2.1	Cold Cast or Chill Roll Cast Process	229
7.2.2	Roll Stack and Calendering Processes	230
7.2.3	Quench Tank or Water Bath Process	230
7.2.4	Nip Rolls and Winding	231
7.2.5	Gauge Control	231
7.2.6	Orientation	232
7.2.7	Cast Film Dies	233
7.3	Blown Film	234
7.3.1	Blown Film Extrusion	236
7.3.2	Blown Film Dies	236
7.3.3	Air Rings and Internal Bubble Cooling (IBC)	239
7.3.4	Collapsing Frames	240
7.3.5	Nips	242
7.3.6	Slitting and Winding	242
7.3.7	Double-Bubble Process	243
7.4	Stretch and Shrink Wrap	244
7.4.1	Stretch Wrap	244
7.4.2	Shrink Wrap	245
7.5	Film and Sheet Coextrusion	246
7.6	Surface Treatment	248
7.7	Yield of Film	249

7.8	Testing and Evaluation of Films	250
7.9	References	251
	Study Questions	251
8	Converting, Lamination and Coating	253
8.1	Extrusion Coating and Laminating	253
8.2	Hot Melt Lamination or Coating	256
8.3	Adhesive Lamination	257
8.4	Thermal Laminating	259
8.5	Metallized Film	259
8.6	Silicon Oxide Films	260
8.7	Other Inorganic Barrier Coatings	261
8.8	Building Multilayer Structures	262
8.9	References	263
	Study Questions	263
9	Flexible Packaging	265
9.1	Characteristics of Flexible Packaging	265
9.2	Pouch Styles	266
9.2.1	Pillow Pouches	266
9.2.2	Three-Side Seal Pouches	267
9.2.3	Four-Side Seal Pouches	267
9.2.4	Stand-Up Pouches	268
9.3	Forming Pouches	269
9.4	Retort Pouches	271
9.5	Bulk and Heavy-Duty Bags	272
9.6	Bag-in-Box	273
9.7	References	274
	Study Questions	274
10	Thermoforming	275
10.1	Introduction	275
10.2	Heating the Sheet	276
10.2.1	Temperature Selection	276
10.2.2	Radiative Heating	276
10.3	Forming the Sheet	278
10.3.1	Basic Methods	278

10.3.1.1	Drape Forming	278
10.3.1.2	Vacuum Forming	279
10.3.1.3	Pressure Forming	279
10.3.2	Sheet Deformation	280
10.3.3	Thermoforming Variations	281
10.3.3.1	Plug-Assist Thermoforming	281
10.3.3.2	Solid Phase Pressure Forming	282
10.3.3.3	Bubble or Billow Forming	282
10.3.3.4	Vacuum Snap-Back Thermoforming	283
10.3.3.5	Matched Mold Forming	283
10.3.3.6	Scrapless Thermoforming	284
10.3.3.7	In-Line Thermoforming and Melt-to-Mold Thermoforming	285
10.3.3.8	Twin-Sheet Thermoforming	285
10.3.3.9	Skin Packaging	285
10.3.4	Selection of Thermoforming Method	286
10.4	Trimming the Sheet	286
10.5	Part and Mold Design	287
10.5.1	Prototype Molds	288
10.5.2	Production Molds	291
10.6	Thermofom-Fill-Seal Systems	291
10.7	References	292
	Study Questions	292
11	Injection Molding, Closures, Rotational Molding, Compression Molding, and Tubes	293
11.1	Injection Molding	293
11.1.1	Injection Molding Machines	293
11.1.2	Injection Mold Units	294
11.1.3	Polymer Flow	296
11.1.4	Removal of Molded Parts	298
11.1.5	Hot Runner Molds	299
11.1.6	Venting	300
11.1.7	Applications of Injection Molding	300
11.2	Closures	300
11.2.1	Friction Closures	301
11.2.2	Snap-Fit Closures	302
11.2.3	Threaded Closures	302
11.2.4	Specialty Closures	304
11.2.5	Fitments and Overcaps	305

11.3	Rotational Molding	305
11.4	Compression Molding	306
11.5	Plastic Tubes	307
11.6	References	308
	Study Questions	308
12	Blow Molding and Bottles	309
12.1	Blow Molding	309
12.2	Extrusion Blow Molding	310
	12.2.1 Basic Extrusion Blow Molding Process	310
	12.2.2 Parison Dimensions	312
	12.2.3 Extrusion Blow Molding Variations	312
	12.2.4 Container Designs	313
	12.2.5 Die Shaping	314
	12.2.6 Programmed Parison	315
	12.2.7 Coextruded Bottles	316
12.3	Injection Blow Molding	318
	12.3.1 IBM Process	318
	12.3.2 Preform Design Process	320
	12.3.3 Comparison of Injection and Extrusion Blow Molding	322
12.4	Stretch Blow Molding	323
	12.4.1 Plastic Soft Drink Bottles	323
	12.4.2 Overview of Stretch Blow Molding	324
	12.4.3 Manufacture of PET Preforms	326
	12.4.4 Bottle Blowing	329
	12.4.4.1 Preform Heating	330
	12.4.4.2 Blowing the Bottles	331
12.5	Liquid Flow Molding	332
12.6	Hot-Fill Bottles	332
12.7	Coinjection Blow Molded Bottles	335
12.8	Foam Blow Molding	337
12.9	Blow Molds	338
12.10	In-Mold Labeling	339
12.11	Aseptic Blow Molding	340
12.12	Surface Treatment	340
	12.12.1 Flame Treatment	341
	12.12.2 Coatings	341
	12.12.3 Fluorination	342
	12.12.4 Sulfonation	342

12.13	Dimensions and Tolerances for Plastic Bottles	342
12.14	References	344
	Study Questions	344
13	Foams, Cushioning, and Distribution Packaging	347
13.1	Foams	347
13.1.1	Polystyrene Foam	348
13.1.1.1	Expanded Polystyrene Foam	348
13.1.1.2	Extruded Polystyrene Foam	349
13.1.1.3	Styrene Copolymer Foams	350
13.1.2	Polyolefin Foams	350
13.1.3	Polyurethane Foams and Foam-in-Place Systems	351
13.1.4	Starch-Based Foams	352
13.2	Nonfoam Plastic Cushioning Systems	352
13.3	Cushioning	353
13.4	Thermal Insulation Using Foams	355
13.5	Plastic Pallets	357
13.6	Plastic Drums and Other Shipping Containers	358
13.7	Packaging for Electrostatic Discharge Protection	359
13.8	References	360
	Study Questions	360
14	Mass Transfer in Polymeric Packaging Systems: Sorption, Diffusion, Permeation, and Shelf Life	361
14.1	Introduction	361
14.2	Physical and Chemical Basis for Interactions	362
14.3	Types of Interactions	363
14.3.1	Permeation	364
14.3.2	Migration	364
14.3.3	Sorption	366
14.4	Thermodynamic Equilibrium	366
14.4.1	Gas Phase Chemical Activity	367
14.4.2	Solubility	368
14.4.3	Partition Coefficient	370
14.5	Diffusion	370
14.6	Steady State Diffusion Across a Single Sheet: Permeability	371
14.7	Variables Affecting Permeability	377
14.7.1	Chemical Structure of the Polymer	377
14.7.2	Chemical Structure of the Permeant Molecule	378

14.7.3	Effect of Temperature	379
14.7.4	Effect of Humidity	382
14.7.5	Physical Structure of the Polymer	383
14.7.6	Effect of Permeant Concentration	386
14.8	Experimental Determination of Permeability	386
14.9	Multilayer Structures	388
14.10	Applications of the Permeability Equation	390
14.11	Shelf Life Estimation	391
14.12	References	397
	Study Questions	398
15	U.S. Regulations and Plastic Packaging	401
15.1	Introduction	401
15.2	The U.S. Federal Food, Drug, and Cosmetic Act	402
15.3	Medical Packaging Regulations	402
15.3.1	Drug Packaging	402
15.3.2	Medical Device Packaging	403
15.4	Food Packaging Regulations	404
15.4.1	What is a Food Additive?	404
15.4.1.1	Example 1: Information on Nylon Available in the CFR	406
15.4.1.2	Example 2: Identification of Relevant Regulations for Fabrication of an Adhesive-Laminated Plastic Bag	406
15.4.2	Global, Specific Migration, and Acceptable Amounts of Migration	407
15.4.3	Threshold of Regulation	410
15.4.4	Food Processing Equipment and the Housewares Exclusion ..	411
15.4.5	Determining the Conditions of Use	412
15.4.6	Multilayer Food Packages	412
15.4.7	GRAS and Prior-Sanctioned Additives	413
15.4.8	Use of Recycled Plastics for Food Packaging	414
15.4.9	Role of Manufacturers and Users in Determining FDA Compliance	416
15.5	Cosmetic Packaging Regulations	417
15.6	State Laws and Regulations	417
15.6.1	Degradable Beverage Carriers	417
15.6.2	“Model Toxics” Legislation	418
15.6.3	Resin Coding on Plastic Bottles	420

15.6.4	Recycling Rate/Recycled Content Requirements	423
15.6.4.1	Oregon	423
15.6.4.2	California	423
15.6.4.3	Wisconsin	424
15.7	Potential Future Issues	424
15.8	References	426
	Study Questions	426
16	Environmental Issues	429
16.1	Introduction	429
16.2	Solid Waste Concerns	430
16.3	Source Reduction and Reuse	435
16.4	Recycling of Plastic Packaging	436
16.4.1	Collection of Packaging Materials for Recycling	437
16.4.2	Recycling Rates for Plastics Packaging	439
16.4.3	Processing of Collected Plastics for Mechanical Recycling	441
16.4.3.1	Size Reduction	441
16.4.3.2	Cleaning	441
16.4.3.3	Sorting	441
16.4.3.4	Extrusion and Pelletizing	443
16.4.4	Feedstock or Chemical Recycling	444
16.5	PET Recycling	445
16.6	HDPE Recycling	446
16.7	LDPE Recycling	448
16.8	Recycling of PS, PP, PVC, and Other Plastics	449
16.9	Recycling of Commingled Plastics	450
16.10	Biodegradable Plastics	451
16.11	Other Environmental Concerns	452
16.11.1	Resource Depletion and Energy Efficiency	452
16.11.2	Pollution	452
16.11.3	Climate Change	453
16.12	Lifecycle Assessment	454
16.13	References	455
	Study Questions	457

17	Additional Reading	459
17.1	Barrier and Mass Transport	459
17.2	Packaging	459
17.3	Packaging Plastics	460
17.4	Plastics	460
17.5	Polymer Processing	461
Index		463