

Contents

- 1 Rubber Compounding: Introduction, Definitions, and Available Resources
 - 1.1 Introduction 7
 - 1.2 The Recipe 9
 - 1.3 Classification of Rubber Compounding Ingredients
 - 1.4 Standard Abbreviations for Compounding Ingredients
 - 1.5 The Diversity of Rubber Recipes
 - 1.6 Compatibility of Compounding Ingredients
 - 1.7 Rubber Compounding Ingredients' Specifications
 - 1.8 Raw Material Source Books
 - 1.9 Key Source References for Formulations
 - 1.10 Technical Organizations
 - 1.11 Key Technical Journals and Trade Magazines
 - 1.12 Regularly Scheduled Technical Conferences
 - 1.12.1 Regularly Scheduled Courses
 - 1.13 Web Sites Available
 - References
- 2 Compound Processing Characteristics and Testing
 - 2.1 Introduction
 - 2.2 Manufacturing Process
 - 2.2.1 Two Roll Mill 17
 - 2.2.2 Internal Mixers 17
 - 2.2.3 Further Downstream Processing 19
 - 2.2.4 Curing Process 20
 - 2.2.5 Factory Problems 20
 - 2.3 Processability Characteristics and Measurements 21
 - 2.3.1 Viscosity 22
 - 2.3.1.1 Rotational Viscometers 22
 - 2.3.1.2 Capillary Rheometer 23
 - 2.3.1.3 Oscillating Rheometers 25
 - 2.3.1.4 Compression Plastimeters 26
 - 2.3.2 Shear Thinning 27
 - 2.3.2.1 Shear Thinning by Capillary Rheometer 28
 - 2.3.2.2 Shear Thinning by Oscillating Rheometer 28
 - 2.3.3 Elasticity 29
 - 2.3.3.1 Mooney Stress Relaxation 31
 - 2.3.3.2 Elasticity by Oscillating Rheometer 32
 - 2.3.3.3 Capillary Rheometer Die Swell 33
 - 2.3.3.4 Compression Plastimeter Elastic Recovery 33
 - 2.3.3.5 Direct Shrinkage Measurements 33
 - 2.3.4 Time to Scorch 33
 - 2.3.4.1 Scorch by Rotational Viscometer 34
 - 2.3.4.2 Scorch by Oscillating Rheometer 34
 - 2.3.4.3 Scorch by Capillary Rheometer 36

2.3.5	Cure Rate	36
2.3.5.1	Cure Rate by Rotational Viscometer	37
2.3.5.2	Cure Times and Cure Rate by Oscillating Rheometer	38
2.3.6	Ultimate State of Cure	39
2.3.6.1	Ring Testing	40
2.3.6.2	Oscillating Rheometer	40
2.3.7	Reversion Resistance	40
2.3.8	Green Strength	41
2.3.9	Tackiness	42
2.3.10	Stickiness	42
2.3.11	Dispersion	42
2.3.12	Stock Storage Stability	43
2.3.13	Mis-Compounding	43
2.3.14	Cellular Rubber Blow Reaction	43
References	. . . . .	44
3	Vulcanizate Physical Properties, Performance Characteristics, and Testing	46
3.1	Introduction	46
3.2	Density	
3.3	Hardness	47
3.4	Tensile Stress-Strain	48
3.5	Stress-Strain Properties under Compression	49
3.6	Stress Strain Properties under Shear	50
3.7	Dynamic Properties	50
3.8	Low Temperature Properties	53
3.8.1	Brittle Point	54
3.8.2	Gehman Test	54
3.9	Stress Relaxation, Creep, and Set	55
3.10	Permeability (Transmission)	57
3.11	Cured Adhesion	57
3.12	Tear Resistance	58
3.13	Degradation Properties	60
3.13.1	Flex Fatigue Resistance	60
3.13.2	Heat Resistance	62
3.13.3	Ozone Resistance	64
3.13.4	Weathering Resistance	65
3.13.5	Resistance to Liquids	65
3.13.6	Abrasion and Wear Resistance	66
References	. . . . .	67
4	Rubber Compound Economics	69
4.1	Introduction	69
4.2	Compound Cost Calculations	69
4.2.1	Specific Gravity	69
4.2.2	Cost/lb	70
4.2.3	Lb-Volume Cost	70
4.2.4	Part Cost	70
4.2.5	Conversion Factors for Calculating Part Cost	70
4.2.5.1	in ³ and cost/lb	70
4.2.5.2	cm ³ and cost/kg	70
4.2.5.3	ft ³ and cost/lb	70
4.2.5.4	cm ³ and cost/lb	71
4.2.5.5	Relative Costs	71
4.2.5.6	Developing Conversion Factors	71
4.3	Measuring Specific Gravity (Density)	72

4.4 Cost Calculations 72

4.4.1 Base Compound 72

4.4.2 Same Ingredient Volume and Equal Cost 73

4.4.3 Low Cost/lb 73

4.4.4 High Specific Gravity 74

4.5 Compound Design and Cost 75

4.6 Reducing Compound Cost 75

4.6.1 High-Structure Carbon Blacks 76

4.6.2 White Compounds 76

4.6.3 Antioxidants/Antiozonants 76

4.6.4 Polymer Substitutions 77

4.6.4.1 High Cost/High Specific Gravity Polymers 77

4.6.4.2 Clear and Oil-Extended Polymer Replacements 77

4.6.4.3 Carbon Black/Oil Masterbatches Replacing Free Mix Compounds 77

4.6.4.4 Extrusion Productivity 81

4.6.4.5 Vulcanization Productivity 82

Appendix 84

5 The Technical Project Approach to Experimental Design and Compound Development

5.1 Introduction 86

5.2 Part 1: Steps in a Technical Project 88

5.2.1 Initial Action Required 88

5.2.1.1 Planning Model 88

5.2.1.2 Work, Time, and Cost Proposal 88

5.2.2 Experimental Design 88

5.2.2.1 Selecting Variables or Factors 88

5.2.2.2 Selecting Test Instruments and Procedures 89

5.2.2.3 Developing a Response Model 89

5.2.2.4 Selecting an Experimental Design 91

5.2.3 Conduct Measurements and Obtain Data 95

5.2.4 Conduct Analysis and Evaluate Preliminary Model 96

5.2.5 Prepare Report 96

5.3 Part 2: Using Experimental Designs 96

5.3.1 Screening Designs – Simple Treatment Comparisons 96

5.3.1.1 Design C1 for Uniform Replication Conditions 97

5.3.1.2 Design C1 for Non-Uniform Replication Conditions 97

5.3.1.3 Design C2 for Multi-Treatment Comparisons 98

5.3.2 Screening Designs – Multifactor Experiments 99

5.3.2.1 Two-Level Factorial Designs 99

5.3.2.2 Analysis of the Designs 100

5.3.2.3 Calculating the Effect Coefficients 101

5.3.2.4 Reviewing Designs S1 to S11 102

5.3.3 Exploratory Designs – Multifactor Experiments 103

5.3.4 Evaluating the Statistical Significance of Effect Coefficients 104

5.3.4.1 Evaluating Standard Errors for Effect Coefficients: Screening Designs 104

5.3.4.2 Four Factor Screening Design: An Example 105

References 110

Appendix 111

6 Elastomer Selection 125

6.1 Overview 125

6.1.1 Commodity and General Purpose Elastomers 125

6.1.1.1 Natural Rubber (NR) 126

6.1.1.2 Styrene-Butadiene Rubber (SBR) 127

Contents

6.1.1.3	Polybutadiene Rubber (BR)	129
	High Volume Specialty Elastomers	130
6.1.2.1	Polyisoprene (IR)	130
6.1.2.2	Nitrile Rubber (NBR)	131
6.1.2.3	Ethylene-Propylene-Diene (EPDM)	132
6.1.2.4	Polychloroprene (CR)	132
6.1.2.5	Butyl and Halogenated Butyl Elastomers	133
6.1.2.6	Chlorinated and Chlorosulfonated Polyethylene	135
	Low Volume Specialty Elastomers	135
6.1.3.1	Fluoroelastomers	135
6.1.3.2	Silicone and Fluorosilicone Rubber	136
6.1.3.3	Polyurethane Rubber	137
6.1.3.4	Ethylene-Acrylic Rubber	137
6.1.3.5	Polyacrylate Rubber	138
6.1.3.6	Epichlorohydrin Rubber	138
6.1.3.7	Polyolefin Elastomers	138
6.1.3.8	Polysulfide Rubber	139
6.1.4	Thermoplastic Elastomers	139
	References	140
7	General Purpose Elastomers and Blends	141
7.1	Introduction	141
7.2	Natural Rubber and Polyisoprene	141
7.3	Polybutadiene	144
7.4	Copolymers and Terpolymers of Styrene, Butadiene, and Isoprene	147
7.5	Compounding with General Purpose Polymers	150
7.5.1	Polymer Characterization and Effect on Mixing	151
7.5.2	Polymer Effect on Cure Rate	153
7.5.3	Polymer Effect on Stress-Strain	156
7.5.4	Hysteresis	157
7.5.5	Compatibility with SIR 10	165
7.5.6	Fatigue Properties	169
7.5.7	Compression Set	170
7.6	Conclusion	171
	References	171
8	Specialty Elastomers	173
8.1	Introduction	173
8.2	Butyl Rubber	173
8.2.1	Introduction	173
8.2.2	Butyl Rubber Physical Properties	174
8.2.3	Butyl Rubber Properties, Vulcanization, and Applications	174
8.2.4	Gas Permeability	175
8.2.5	Ozone and Weathering Resistance	176
8.2.6	Butyl Rubber Vulcanization	176
8.2.6.1	Accelerated Sulfur Vulcanization	177
8.2.6.2	The Dioxime Cure	177
8.2.6.3	The Resin Cure	177
8.3	Halogenated Butyl Rubber	178
8.3.1	Introduction	178
8.3.2	Compounding Halobutyl and Star-Branched Halobutyl Rubbers	179
8.3.2.1	Carbon Black	179
8.3.2.2	Mineral Fillers	180
8.3.2.2	Plasticizers	180
8.3.2.3	Processing Aids	180

8.3.3	Processing Halobutyl Rubber	181
8.3.3.1	Mixing	181
8.3.3.2	Calendering	181
8.3.3.3	Extrusion	182
8.3.3.4	Molding	182
8.3.4	Halobutyl Rubber Vulcanization and Applications	182
8.3.4.1	Straight Sulfur Cure	183
8.3.4.2	Zinc Oxide Cure and Modifications	183
8.3.4.3	Zinc-Free Cures	183
8.3.4.4	Peroxide Cures	183
8.3.4.5	Vulcanization through Bis-Alkylation	184
8.3.4.6	Resin Cure	184
8.3.4.7	Scorch Control	184
8.3.4.8	Stability of Halobutyl Crosslinks	185
8.3.5	Halobutyl Rubber General Applications	185
8.3.6	Cured Properties	186
8.3.6.1	Permeability	186
8.3.6.2	Heat Resistance	186
8.3.6.3	Resistance to Chemicals and Solvents	186
8.3.7	Flex Resistance/Dynamic Properties	186
8.3.8	Compatibility with Other Elastomers	187
8.3.9	Halobutyl Rubber Compound Applications	187
8.3.9.1	Tire Innerliners	187
8.3.9.2	Pharmaceutical Closures	187
8.3.9.3	Heat Resistant Conveyor Belt	188
	References	189
8.4	EPM/EPDM	190
8.4.1	Introduction	190
8.4.2	Ethylene/Propylene Content	190
8.4.3	Diene Content	191
8.4.4	Rheology	192
	Reference	192
8.5	Acrylonitrile-Butadiene Rubber	
8.5.1	Introduction	
8.5.2	Chemical and Physical Properties – Relating to Application	193
8.5.2.1	Acrylonitrile Content (ACN)	194
8.5.2.2	Mooney Viscosity	194
8.5.2.3	Emulsifier	
8.5.2.4	Stabilizer	
8.5.2.4	Coagulation	195
8.5.3	Polymer (Elastomer) Microstructure	196
8.5.4	Polymer (Elastomer) Macrostructure	196
8.5.5	Gel	196
8.5.6	Molecular Weight	197
8.5.7	Hot NBR	197
8.5.8	Crosslinked Hot NBR	
8.5.9	Cold NBR	
8.5.10	Carboxylated Nitrile (XNBR)	198
8.5.11	Bound Antioxidant NBR	199
	Acknowledgement	200
	References	200
8.6	Hydrogenated Nitrile Butadiene Elastomers	201
8.6.1	Introduction	201
8.6.2	Applications	202
8.6.3	Properties	202

8.6.4	Formulating	202
8.6.5	Processing	203
8.7	Polyacrylate Elastomers	203
8.7.1	Polymer Composition	203
8.7.2	Basic Compounding of Polyacrylate Polymers	205
8.7.3	Processing Guidelines	206
	References	207
8.8	Polychloroprene (Neoprene)	207
8.8.1	Introduction	207
8.8.2	Basic Characteristics of Polychloroprene	208
8.8.3	Families of Neoprene	208
8.8.4	Neoprene 'G' Family	208
8.8.5	Neoprene 'W' Family	210
8.8.6	Neoprene 'T' Family	211
8.9	Chlorinated Polyethylene (CM)	211
8.9.1	Introduction	211
8.9.2	General Characteristics	212
8.10	Chlorosulfonated Polyethylene (CSM)	213
8.10.1	Introduction	213
8.10.2	General Purpose Types of Hypalon	215
8.10.3	Specialty Types of Hypalon	215
8.10.4	Unvulcanized Applications	216
8.11	Polyepichlorohydrin Elastomer	216
8.11.1	Introduction	216
8.11.2	Properties	216
8.11.3	Formulating	217
8.11.4	Nonlead Cure Systems	218
8.11.5	Adjustments	218
8.11.6	Processing	218
8.11.7	Internal Mixer – Procedure	219
8.11.8	Extrusion	219
8.11.9	Molding	219
	Reference	221
8.12	Ethylene-Acrylic Elastomers	221
8.12.1	Introduction	221
8.12.2	Polymer Composition and Effect on Properties	222
8.12.3	Polymer Selection	223
8.13	Polynorbornene	224
8.13.1	Introduction	224
8.13.2	Applications	224
8.13.3	Compounding	225
8.13.4	Fillers	225
8.13.5	Oils/Plasticizers	225
8.13.6	Cure System	225
8.13.7	Rebound/Resilience	226
8.13.8	Vibration Damping	226
8.13.9	Blends	226
8.13.10	Mixing and Processing	226
	8.13.10.1 Mill Mixing	226
	8.13.10.2 Internal Mixers	227
8.13.11	Calendering	227
8.13.12	Extrusion	227
8.13.13	Molding	229
8.13.14	Summary	229
	Reference	229

8.14	Fluoroelastomer (FKM)	229
8.14.1	Introduction	229
8.14.2	Background	229
8.14.3	Applications	231
8.14.4	Viton Types	231
8.15	Silicone Elastomers	235
8.15.1	Introduction	235
8.15.2	Selection	235
8.15.3	Fillers	235
8.15.4	Antistructuring Agents	236
8.15.5	Heat Stabilizers	236
8.15.6	Peroxide Cures	236
8.15.7	Platinum Cures	237
8.15.8	RTV Cures	237
9	Polyurethane Elastomers	238
9.1	Introduction	238
9.2	Polyurethane Chemistry and Morphology	238
9.3	Polyurethane Products	241
9.4	Cast Polyurethane Processing Overview	242
9.5	Molding Methods	244
9.5.1	Open Casting	244
9.5.2	Centrifugal Molding	245
9.5.3	Vacuum Casting	245
9.5.4	Compression Molding	245
9.5.5	Transfer Molding	245
9.5.6	Liquid Injection Molding (LIM)	246
9.5.7	Spraying	246
9.5.8	Moldless Rotational Casting	246
9.6	How to Select a Polyurethane Elastomer	246
9.6.1	Types of Prepolymers	247
9.6.2	Types of Curatives	249
9.6.3	Processing Conditions	250
9.6.4	Additives	252
9.7	Comparison of Polyurethanes with Other Elastomers	253
9.7.1	Limitations of Polyurethane Elastomers	255
9.8	Polyurethane Selection Guidelines	257
9.8.1	Selecting a Polyurethane Elastomer for a New Application	260
9.9	Millable Gums	261
9.10	Thermoplastic Polyurethanes	262
	References	262
	General References	263
10	Thermoplastic Elastomers	264
10.1	Introduction	264
10.2	Position in Spectrum of Polymeric Materials	264
10.3	Classification of TPEs	265
10.3.1	Chemistry and Morphology	265
10.3.2	Styrenic Block Copolymers	268
10.3.3	Copolyesters	270
10.3.4	Thermoplastic Polyurethanes	271
10.3.5	Polyamides	272
10.3.6	Thermoplastic Elastomeric Olefins	273
10.3.7	Thermoplastic Vulcanizates	274

10.4	TPEs and Thermoset Rubbers	276
10.5	Fabrication of TPEs	278
10.5.1	Economy of Thermoplastics Processing	278
10.5.2	Injection Molding	278
10.5.3	Extrusion	278
10.5.4	Blow Molding	280
10.5.5	Other Processing Methods	281
10.6	Acknowledgments	281
	References	281
11	Recycled Rubber	284
11.1	Introduction	284
11.1.1	Tire Derived Fuel	284
11.1.2	Automotive Industry's Recycling Efforts	285
11.2	Recycling Methods	286
11.2.1	Reclaiming	286
11.2.2	Ambient Ground Rubber	287
11.2.3	Cryogenic Ground Rubber	288
11.2.4	Wet Ground Rubber	292
11.2.5	Surface Treatment and Additives for Producing Recycled Rubber	292
11.3	Testing, Storage, and Characterization	292
11.3.1	Testing Standards	292
11.3.2	Material Storage	293
11.3.3	Moisture Content	293
11.3.4	Bulk Density	293
11.3.5	Chemical Analysis and Material Specifications	293
11.3.6	Particle Size and Distribution	294
	References	296
12	Compounding with Carbon Black and Oil	297
12.1	Introduction: Carbon Black Affects Everything	297
12.2	Characterization of Carbon Black	297
12.2.1	The Particle, the Aggregate, and the Agglomerate	298
12.2.2	Surface Area, Structure, and Surface Activity	298
12.2.3	Constituents Other than Carbon (Impurities)	300
12.2.4	Pellets	301
12.2.5	ASTM Nomenclature	301
12.3	Handling Carbon Black	303
12.4	Mixing Carbon Black	303
12.4.1	Pellet Properties and Analyticals (also called Colloidal Properties)	303
12.4.2	Effect of Analyticals on Dispersion	303
12.4.3	The Mixing Process	304
12.5	Subsequent Processability of the Compound	306
12.6	Compounding Carbon Black	306
12.6.1	Optimum Loading	306
12.6.2	Importance of Dispersion	309
12.6.3	Carbon Black Compounding Tips	310
12.6.3.1	Hardness	310
12.6.3.2	Processing Oil	311
12.6.3.3	Other Vulcanizate Properties	312
12.6.3.4	Vulcanizate Hysteresis	312
12.6.4	The Tire Industry's Tradeoffs	314
12.7	Hysteresis Reducing Tips	316
12.7.1	"Radical Compounding"	316
12.7.2	Lower Loadings of High Structure Carbon Blacks	317

12.7.3	Carbon-Silica Dual Phase Fillers	318
12.8	Practical Applications: Tire Examples	318
12.8.1	OE Passenger-Tire Treads	318
12.8.2	Replacement Passenger-Tire Treads	318
12.8.3	HP Passenger-Tire Treads	319
12.8.4	Medium Radial Truck Treads	319
12.8.5	Wire Coat or Skim Stocks	319
12.8.6	Innerliner Compounding	319
12.9	Major Tradeoffs for Industrial Rubber Products	320
12.9.1	Loading/Reinforcement/Cost	320
12.10	Compounding Tips: Industrial Rubber Products	320
12.10.1	Extrusion Profiles and Products	320
12.10.2	Molded Products	321
12.10.3	Hose Applications	321
12.11	Basics of Carbon Black Manufacture	322
12.11.1	History	322
12.11.2	The Oil-Furnace Process	322
	References	324
13	Precipitated Silica and Non-Black Fillers	325
13.1	Introduction	325
13.2	Mineral Fillers	325
13.2.1	Calcium Carbonate	326
13.2.2	Baryte	326
13.2.3	Ground Crystalline Silica	326
13.2.4	Biogenic Silica	327
13.2.5	Kaolin Clay	327
13.2.6	Talc	328
13.2.7	Alumina Trihydrate	328
13.3	Synthetic Fillers	328
13.3.1	Precipitated Calcium Carbonate	329
13.3.2	Metal Oxides	329
13.3.3	Precipitated Silica	329
13.3.4	Silicates	331
13.4	Surface Treatment	331
13.5	Compound Applications	332
13.5.1	General Compounding Principles	333
13.5.2	White Sidewall	334
13.5.3	Black Sidewall	336
13.5.4	Wire Coat	336
13.5.5	Innerliner	339
13.5.6	Tread	340
13.5.7	Specialty Applications	341
	References	342
14	Ester Plasticizers and Processing Additives	344
14.1	Ester Plasticizers for Elastomers	344
14.1.1	Derivation	344
14.1.2	Philosophical	347
14.1.3	Applications	348
14.1.3.1	Low-ACN Content NBR	349
14.1.3.2	Neoprene Blend GN 88/WHV 12	350
14.1.3.3	Different Elastomers with the Same Plasticizer	351
14.1.3.4	Medium Acrylonitrile-Content NBR	352

14.1.3.5	Medium ACN NBR	352
14.1.3.6	Medium-High ACN-Content NBR	355
14.1.3.7	NBR/PVC Polyblends	356
14.1.3.8	Ethylene Acrylic and Polyacrylate Elastomers	357
14.1.3.9	Chlorosulfonated Polyethylene (CSM)	358
14.1.3.10	Chlorinated Polyethylene (CPE)	358
14.1.4	Application Trends	360
14.2	Process Additives	363
14.2.1	Control of Viscosity	364
14.2.1.1	Viscosity Control of Natural Rubber	364
14.2.1.2	Viscosity Control of Synthetic Rubber	367
14.2.2	Mode of Action of Process Additives	369
14.2.2.1	Surface Lubricants	371
14.2.2.2	Process Additives for Homogenizing and Improving Filler Dispersion	372
14.2.3	Application of Process Additives	373
	References	376
15	Sulfur Cure Systems	380
15.1	Introduction and Historical Background	380
15.2	Vulcanizing Agents	381
15.3	Activators	382
15.4	Accelerators	383
15.5	Conventional, Semi-Efficient and Efficient Cures	386
15.6	Retarders and Inhibitors	387
15.7	Recent Developments	389
	References	394
16	Cures for Specialty Elastomers	395
16.1	Introduction	395
16.2	Cure Systems for EPDM	395
16.3	Cure Systems for Nitrile	397
16.4	Cure Systems for Polychloroprene	400
16.5	Cure Systems for Butyl and Halobutyl Rubber	402
	References	410
17	Peroxide Cure Systems	411
17.1	Introduction	411
17.1.1	What is an Organic Peroxide?	411
17.1.2	Classes of Organic Peroxides	411
17.1.3	General Peroxide Selection Guidelines	412
17.1.3.1	Half-Life	413
17.1.3.2	Minimum Cure Time	413
17.1.3.3	SADT (Self Accelerating Decomposition Temperature)	414
17.1.3.4	Maximum Storage Temperature (MST)	414
17.1.3.5	Energy of Peroxide Free Radicals	414
17.1.3.6	Peroxide Polymer Masterbatches	417
17.1.3.7	High Performance (HP) Peroxide Formulations for Improved Productivity	418
17.2	Peroxides Used in Crosslinking	420
17.2.1	Diacyl Peroxides	421
17.2.2	Peroxyester and Monoperoxy carbonate Peroxides	422
17.2.3	Peroxyketal and Dialkyl Type Peroxides	422
17.2.4	Performance Characteristics of Dialkyl Type Peroxides	426
17.2.5	t-Amyl and t-Butyl Type Peroxides	428
17.2.6	Effect of Additives When Crosslinking with Peroxides	430

17.3	Role of Monomeric Coagents in Peroxide Crosslinking	430
17.3.1	Crosslinking PE with Coagents and Peroxides	432
17.3.2	Crosslinking EPDM with Coagents and Peroxides	433
17.3.3	Crosslinking HNBR with Coagents and Peroxides	434
17.4	Advantages and Disadvantages of Peroxide Crosslinking versus Sulfur Vulcanization	434
	References	436
18	Tackifying, Curing, and Reinforcing Resins	438
18.1	Introduction	438
18.2	Phenol-Formaldehyde Resins	438
18.2.1	Types of Phenol-Formaldehyde Resins	439
18.2.1.1	Reinforcing Resins	439
18.2.1.2	Tackifying Resins	443
18.2.1.3	Curing Resins	443
18.3	Methylene Donor Resins	445
18.4	Resorcinol-Based Resins	446
18.5	High Styrene Resins	446
18.6	Petroleum-Derived Resins	446
18.7	Wood-Derived Resins	446
	References	447
	Abbreviations	447
19	Antidegradants	448
19.1	Introduction	448
19.2	Properties of Antidegradants	449
19.2.1	Discoloration and Staining	449
19.2.2	Volatility	449
19.2.3	Solubility and Migration	449
19.2.4	Chemical Stability	450
19.2.5	Physical Form	451
19.2.6	Antidegradant Concentration	451
19.3	Antidegradant Types	451
19.3.1	Non-Staining, Non-Discoloring Antioxidants	452
19.3.1.1	Hindered Phenols	452
19.3.1.2	Hindered “Bis” Phenols	452
19.3.1.3	Substituted Hydroquinones	452
19.3.1.4	Phosphites	453
19.3.1.5	Organic Sulfur Compounds	453
19.3.1.6	Hindered Amine and Nitroxyl Compounds	453
19.3.2	Staining/Discoloring Antioxidants	454
19.3.2.1	Phenylnaphthylamines	454
19.3.2.2	Dihydroquinolines	454
19.3.2.3	Diphenylamine Derivatives	455
19.3.2.4	Substituted Paraphenylenediamines (PPDs)	455
19.3.2.5	Amine-based, “Bound-in” or “Polymer Bound” Antioxidants	455
19.3.3	Antiozonants	456
19.3.3.1	Petroleum Waxes	456
19.3.3.2	Nickel Dibutyldithiocarbamate (NBC)	457
19.3.3.3	6-Ethoxy-2,2,4-trimethyl-1,2-dihydroquinoline (ETMQ)	457
19.3.3.4	Substituted Paraphenylenediamines (PPDs)	457
19.4	Examples of Antidegradant Activity	458
19.4.1	Oxidation Resistance	458
19.4.2	Effect of Antidegradants on Fatigue Life	458
19.4.3	Combinations of Antiozonants and Antioxidants	460

19.4.4	Resistance to Metal Poisoning	461
References		462
Abbreviations		463
20	Compounding for Brass Wire Adhesion	464
20.1	Introduction	464
20.2	Wire Bonding Systems	464
20.2.1	Cobalt	465
20.2.2	RF Resin-Cobalt	465
20.3	The Adhesion Mechanism	466
20.4	Compound Ingredient Effects	466
20.4.1	Mixing	467
20.4.2	Testing	467
20.4.3	Regression Plots	468
20.4.3.1	Carbon Black	468
20.4.3.2	Zinc Oxide/Stearic Acid	469
20.4.3.3	Sulfur/DCBS	469
20.4.3.4	Cobalt	470
20.4.3.5	RF Resin/HMMM	471
20.4.3.6	Carbon Black/Silica	472
20.4.3.7	Summary of Test Results	472
20.5	Model NR Ply Compounds	473
20.5.1	Black Control Compound	473
20.5.2	Black/Cobalt Compound	473
20.5.3	Black/Cobalt/RF Resin	474
20.5.4	Black/Silica/Cobalt/RF Resin	474
20.6	Summary	474
Acknowledgments		474
References		474
21	Chemical Blowing Agents	476
21.1	Introduction	476
21.2	Terminology	476
21.2.1	Open Cell Structure	477
21.2.2	Closed Cell Structure	477
21.3	Inorganic Blowing Agents	478
21.4	Organic Blowing Agents	478
21.4.1	Azodicarbonamide (ADC)	479
21.4.1.1	Properties	480
21.4.1.2	Activation	480
21.4.1.3	Factors Affecting Performance	480
21.4.1.4	Effect of Particle Size	481
21.4.1.5	Effect of Temperature	483
21.4.1.6	ADC Activation and Cell Size	483
21.4.2	Sulfonyl Hydrazides	484
21.4.2.1	Properties	484
21.4.2.2	Activation	484
21.4.2.3	Applications	484
21.4.3	Dinitrosopentamethylenetetramine (DNPT)	484
21.4.3.1	Properties	485
21.4.3.2	Activation	485
21.5	Methods of Expansion	486
21.5.1	Low Pressure Molding Process	486
21.5.2	High Pressure Molding Process	486

21.5.2.1	Precure Stage	486
21.5.2.2	Final Cure Stage	487
21.5.3	Continuous Vulcanization (CV)	487
References	. . . . .	487
22	Flame Retardants	489
22.1	Introduction	489
22.2	Fire Standards, Testing, and Applications	489
22.3	Commonly Used Flame Retardants in Elastomers	491
22.3.1	Aliphatic and Alicyclic Halogen Sources	491
22.3.2	Aromatic Halogen Sources	491
22.3.3	Synergists of Halogen Sources	491
22.3.3.1	Antimony Oxide	491
22.3.3.2	Zinc Borate	492
22.3.3.3	Phosphorus Compounds	492
22.3.4	Flame Retardant Fillers	492
22.3.4.1	Alumina Trihydrate (ATH)	492
22.3.4.2	Magnesium Hydroxide	492
22.3.4.3	Calcium Carbonate	493
22.3.4.4	Clay, Talc, and Silica	493
22.3.4.5	Carbon Black	493
22.4	Compounding and Dispersion Considerations	493
22.4.1	Polychloroprene (CR)	494
22.4.2	Chlorinated Polyethylene (CM)	495
22.4.3	Chlorosulfonated Polyethylene (CSM)	496
22.4.4	Ethylene-Propylene-Diene-Monomer (EPDM)	496
22.4.5	Styrene-Butadiene (SBR)	499
22.4.6	Nitrile-Butadiene Rubber (NBR) and Hydrogenated-Nitrile-Butadiene Rubber (HNBR)	499
22.4.7	Silicone Elastomer	500
22.4.8	Ethylene-Vinyl Acetate (EVM)	501
22.4.9	Ethylene-Propylene Elastomer (EPR)	502
22.4.10	Thermoplastic Elastomers (TPE)	502
Acknowledgments	. . . . .	502
References	. . . . .	502
23	Rubber Mixing	504
23.1	Introduction	504
23.2	History	504
23.3	Equipment	505
23.3.1	Mills	505
23.3.2	Internal Mixers	505
23.3.2.1	Tangential Rotor Type	506
23.3.2.2	Intermeshing Rotor Type	506
23.3.2.3	Variable Internal Clearance Mixer	507
23.3.2.4	Continuous Mixers	508
23.3.2.5	Extruders	508
23.4	Mixing	510
23.4.1	Mill Mixing	510
23.4.2	Internal Mixer	511
23.4.2.1	Batch Size	511
23.4.2.2	Batch Conversion Factor	512
23.4.2.3	Density and Cost Calculations	512
23.4.2.4	Mixing Procedures	513
23.4.2.5	Mixing Temperatures	514

23.5	Mixing Methods	514
23.5.1	Natural Rubber Mastication	514
23.5.2	Masterbatch Mixing	515
23.5.3	Phase Mixing	515
23.5.4	Single-Stage Mix	517
23.5.5	Single-Cycle Mix	517
23.5.6	Two-Stage Mix	517
23.5.7	Tandem Mixing	517
23.5.8	Three-Stage Mix	518
23.5.9	Upside Down Mix	518
23.5.10	Variable Speed Mixing	518
23.5.11	Final Mix	519
23.5.12	Continuous Mixing	520
23.5.13	E-SBR Carbon Black Masterbatch	520
23.5.14	Energy Mixing	521
References	. . . . .	522
Index		523