Contents

Preface XV

1 1.1 1.2 1.3 1.4	Colloids in Paints 1 The Disperse Particles 2 The Dispersion Medium and Film Formers 5 Deposition of Particles and Their Adhesion to the Substrate 8 Flow Characteristics (Rheology) of Paints 8 References 9
2	Emulsion, Dispersion and Suspension Polymerization: Preparation of Polymer Colloids and Their Stabilization 11
2.1	Emulsion Polymerization 11
2.1.1	Mechanism of Emulsion Polymerization 14
2.1.2	Block Copolymers as Stabilizers in Emulsion Polymerization 15
2.1.3	Graft Copolymers as Stabilizers in Emulsion Polymerization 18
2.2	Polymeric Surfactants for Stabilization of Preformed Latex Dispersions 23
2.3	Dispersion Polymerization 27
2.3.1	Mechanism of Dispersion Polymerization 29
2.3.2	Influence of Polymeric Surfactant Concentration and Molecular Weight on Particle Formation 30
2.3.3	Effect of Monomer Solubility and Concentration in the Continuous Phase 30
2.3.4	Stability/Instability of the Resulting Latex 31
2.3.5	Particle Formation in Polar Media 31 References 32
3.1.1 3.1.1 3.1.2 3.1.3 3.1.4	Pigment Dispersion 33 Powder Wetting 33 Wetting of Substrates 33 Adhesion Tension 36 Work of Adhesion, W _a 36 The Work of Cohesion 37

Colloids and Interface Science Series, Vol. 6 Colloids in Paints. Tharwat F. Tadros Copyright © 2010 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim ISBN: 978-3-527-31466-9

'III	Contents	
•	3.1.5	Spreading Coefficient, S 37
	3.1.6	Contact Angle Hysteresis 38
	3.1.7	Reasons for Hysteresis 38
	3.1.8	Wenzel's Equation 39
	3.1.9	Surface Heterogeneity 39
	3.1.10	Critical Surface Tension of Wetting 40
	3.1.11	Effect of Surfactant Adsorption 41
	3.1.12	Wetting of Powders by Liquids 42
	3.1.13	Rate of Penetration of Liquids. The Rideal–Washburn Equation 44
	3.1.14	Measurement of Wettability of Powders 44
	3.1.14.1	Submersion Test – Sinking Time or Immersion Time 44
	3.1.14.2	Measurement of Contact Angles of Liquids and Surfactant Solutions on Powders 45
	3.1.15	Wetting Agents for Hydrophobic Pigments 46
	3.1.16	Adsorption and Wetting Dynamics 48
	3.1.17	General Theory of Adsorption Kinetics 48
	3.1.17.1	Adsorption Kinetics from Micellar Solutions 51
		Experimental Techniques for Studying Adsorption Kinetics 52
	3.2	Breaking of Aggregates and Agglomerates (Deagglomeration) 56
	3.2.1	Classification of Dispersants 57
	3.2.2	Assessment and Selection of Dispersants 60
	3.2.2.1	Adsorption Isotherms 60
	3.2.3	Measurement of Dispersion and Particle Size Distribution 62
	3.2.3.1	Optical Microscopy 62
	3.2.3.2	Electron Microscopy 63
	3.2.3.3	Confocal Scanning Laser Microscopy (CLSM) 64
	3.2.3.4	Scattering Techniques 64
	3.3	Wet Milling (Comminution) 67
	3.3.1	Bead Mills 69
	3.3.2	Principle of Operation of Bead Mills 69
		References 70
	4	Colloid Stabilization of Paint Dispersions 71
	4.1	Electrostatic Double Layer Repulsion 71
	4.1.1	Structure of the Solid/Liquid Interface – Origin of Charges on Surfaces 71
	4.1.2	Structure of the Electrical Double Layer 73
	4.1.2.1	Diffuse Double layer (Gouy and Chapman) 73
	4.1.2.2	Stern–Grahame Model of the Double Layer 74

Electrical Double Layer Repulsion 75

Deryaguin-Landau-Verwey-Overbeek (DLVO) Theory

Flocculation of Electrostatically Stabilized Suspensions

78

Van der Waals Attraction 76

Total Energy of Interaction 78

4.1.3 4.1.4

4.2

4.2.1

4.2.2

4.2.3	Criteria for Stabilization of Dispersions with Double Layer Interaction 82			
4.2.4	Electrokinetic Phenomena and Zeta Potential 82			
4.2.5	Calculation of Zeta Potential 84			
4.2.5.1	Von Smoluchowski (Classical) Treatment 84			
4.2.5.2	The Hückel Equation 85			
4.2.5.3	Henry's Treatment 85			
4.2.6	Measurement of Electrophoretic Mobility 86			
4.2.6.1	Ultramicroscopic Technique (Microelectrophoresis) 86			
4.2.6.2	Laser Velocimetry Technique 86			
4.3	Adsorption and Conformation of Polymeric Surfactants at Interfaces 87			
4.3.1	Theories of Polymer Adsorption 90			
4.3.2	Experimental Techniques for Studying Polymeric Surfactant			
7.5.2	Adsorption 93			
4.3.2.1	Measurement of the Adsorption Isotherm 93			
4.3.2.2	Measurement of the Fraction of Segments <i>p</i> 94			
4.3.2.3	Determination of the Segment Density Distribution $\rho(z)$ and Adsorbed			
	Layer Thickness $\delta_{ m h}$ 94			
4.3.3	Examples of the Adsorption Isotherms of Nonionic Polymeric			
	Surfactants 96			
4.4	Interaction Between Particles Containing Adsorbed Polymeric			
	Surfactant Layers 101			
4.4.1	Steric Stabilization 101			
4.4.2	Mixing Interaction $G_{\rm mix}$ 102			
4.4.3	Elastic Interaction $G_{\rm el}$ 103			
4.4.4	Criteria for Effective Steric Stabilization 105			
4.4.5	Flocculation of Sterically Stabilized Dispersions 105			
	References 107			
_	Postiola Danasition and Adhasian 100			
5	Particle Deposition and Adhesion 109			
5.1	Deposition of Particles on Surfaces 109			
5.1.1	Van der Waals Attraction 109			
5.1.2	Electrostatic Repulsion 110			
5.1.3	Effect of Polymers and Polyelectrolytes on Particle Deposition 114			
5.1.4	Effect of Nonionic Polymers on Particle Deposition 115			
5.1.5	Effect of Anionic Polymers on Particle Deposition 116			
5.1.6	Effect of Cationic Polymers on Particle Deposition 117			
5.2	Particle–Surface Adhesion 117			
5.2.1	Surface Energy Approach to Adhesion 118			
5.2.1.1	Fox and Zisman Critical Surface Tension Approach 119			
5.2.1.2	Neuman's Equation of State Approach 119			
5.2.2	Experimental Methods for Measurement of Particle-Surface			
	Adhesion 120			

х	Contents	
	5.2.2.1	Centrifugal Method (Krupp, 1967) 120
	5.2.2.2	Hydrodynamic Method (Visser, 1970) 120
		References 121
	6	Basic Principles of Rheology 123
	6.1	Principles of Steady-state Measurements 123
	6.1.1	Strain Rate or Shear Rate 124
	6.1.2	Types of Rheological Behavior in Simple Shear 125
	6.1.3	Models for Flow Behavior 125
	6.1.3.1	Law of Elasticity (Hooke's Model) 125
	6.1.3.2	Newton's Law of Viscosity 125
	6.1.3.3	Non-Newtonian Flow 126
	6.1.4	Rheological Models for Analysis of Flow Curves 127
	6.1.4.1	Newtonian Systems 127
	6.1.4.2	Bingham Plastic Systems 128
	6.1.4.3	Pseudoplastic (Shear Thinning) System 128
	6.1.4.4	Dilatant (Shear Thickening) System 128
	6.1.4.5	Herschel–Bulkley General Model 128
	6.1.4.6	The Casson Equation 129
	6.1.4.7	The Cross Equation 129
	6.1.5	Time Effects During Flow – Thixotropy and Negative (or Anti-)
		Thixotropy 130
	6.1.6	Rheopexy 132
	6.1.7	Measurement of Viscosity as a Function of Shear Rate – Steady-state
		Regime 132
	6.1.8	Capillary Viscometers 133
	6.1.9	Measurement of Intrinsic Viscosity of Polymers 134
	6.1.10	Capillary Rheometry for Non-Newtonians 135
	6.1.11	Rotational Viscometers 136
	6.1.12	Concentric Cylinder Viscometer 136
	6.1.13	Non-Newtonians 137
		Shear Thinning or Pseudoplastic 137
		Bingham Plastic 138
	6.1.14	Major Precautions with Concentric Cylinder Viscometers 138
		Shear Rate Calculations 138
		Wall Slip and Sample Evaporation During Measurement 139 The Vane Rheometer 139
		Cone and Plate Rheometer 140
		Parallel Plates (Disks) 141
		The Brookfield Viscometer 141

Principles of Viscoelastic Behavior 143

Strain Relaxation After Sudden Application of Stress (Creep) 144

Introduction 143

The Deborah Number 144

Analysis of Creep Curves 145

6.2

6.2.1

6.2.2

6.2.3

6.2.1.1

6.2.3.1	Viscous Fluid 145				
6.2.3.2	Elastic Solid 146				
6.2.4	Viscoelastic Response 146				
6.2.4.1	Viscoelastic Liquid 146				
6.2.4.2	Viscoelastic Solid 147				
6.2.5	The Berger Model (Maxwell + Kelvin) 148				
6.2.6	Creep Procedure 149				
6.2.7	Stress Relaxation After Sudden Application of Strain 150				
6.2.8	Dynamic (Oscillatory) Techniques 153				
6.2.8.1	Analysis of Oscillatory Response for a Viscoelastic System 154				
6.2.8.2	Vector Analysis of the Complex Modulus 155				
6.2.9	Strain Sweep 156				
6.2.10	Oscillatory Sweep 156				
6.2.11	The Cohesive Energy Density, E_c 158				
6.2.12	Viscoelastic Measurements 158				
6.2.12.1	Constant Stress (Creep) Measurements 158				
6.2.12.2	Stress Relaxation (After Application of Constant Strain) 160				
6.2.12.3	Dynamic (Oscillatory) Measurements 161				
6.2.12.4	Shear Modulus (Rigidity) Measurement 162				
	References 163				
7	Rheology of Suspensions, Emulsions and Their Mixtures				
	(C				
	(Suspoemulsions) 165				
7.1	Rheology of Suspensions 165				
7.1.1	Rheology of Suspensions 165 Introduction 165				
7.1.1 7.1.2	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165				
7.1.1 7.1.2 7.1.3	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165 The Batchelor Equation 166				
7.1.1 7.1.2 7.1.3 7.1.4	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165 The Batchelor Equation 166 Rheology of Concentrated Suspensions 166				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165 The Batchelor Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165 The Batchelor Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165 The Batchelor Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165 The Batchelor Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8 7.1.9	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165 The Batchelor Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170 Rheology of Sterically Stabilized Dispersions 171				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8 7.1.9 7.1.10	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165 The Batchelor Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170 Rheology of Sterically Stabilized Dispersions 171 Rheology of Flocculated Suspensions 171				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8 7.1.9 7.1.10 7.1.10.1	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165 The Batchelor Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170 Rheology of Sterically Stabilized Dispersions 171 Rheology of Flocculated Suspensions 171 Weakly Flocculated Suspensions 172				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8 7.1.9 7.1.10 7.1.10.1	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165 The Batchelor Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170 Rheology of Sterically Stabilized Dispersions 171 Rheology of Flocculated Suspensions 172 Strongly Flocculated (Coagulated) Suspensions 173				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8 7.1.9 7.1.10 7.1.10.1 7.1.10.2 7.1.11	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170 Rheology of Sterically Stabilized Dispersions 171 Rheology of Flocculated Suspensions 171 Weakly Flocculated Suspensions 172 Strongly Flocculated (Coagulated) Suspensions 173 Analysis of the Flow Curve 174				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8 7.1.9 7.1.10 7.1.10.1 7.1.10.2 7.1.11	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165 The Batchelor Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170 Rheology of Sterically Stabilized Dispersions 171 Rheology of Flocculated Suspensions 171 Weakly Flocculated Suspensions 172 Strongly Flocculated (Coagulated) Suspensions 173 Analysis of the Flow Curve 174 Impulse Theory: Goodeve and Gillespie 174				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8 7.1.9 7.1.10 7.1.10.1 7.1.10.1 7.1.11.2	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 165 The Batchelor Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170 Rheology of Sterically Stabilized Dispersions 171 Rheology of Flocculated Suspensions 171 Weakly Flocculated Suspensions 172 Strongly Flocculated (Coagulated) Suspensions 173 Analysis of the Flow Curve 174 Impulse Theory: Goodeve and Gillespie 174 Elastic Floc Model: Hunter and Co-workers 174				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8 7.1.9 7.1.10 7.1.10.1 7.1.10.2 7.1.11 7.1.11.1 7.1.11.2	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170 Rheology of Sterically Stabilized Dispersions 171 Rheology of Flocculated Suspensions 171 Weakly Flocculated Suspensions 172 Strongly Flocculated (Coagulated) Suspensions 173 Analysis of the Flow Curve 174 Impulse Theory: Goodeve and Gillespie 174 Elastic Floc Model: Hunter and Co-workers 174 Fractal Concept of Flocculation 175				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8 7.1.9 7.1.10 7.1.10.1 7.1.10.2 7.1.11 7.1.11.1 7.1.11.2 7.1.12	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170 Rheology of Sterically Stabilized Dispersions 171 Rheology of Flocculated Suspensions 171 Weakly Flocculated Suspensions 172 Strongly Flocculated (Coagulated) Suspensions 173 Analysis of the Flow Curve 174 Impulse Theory: Goodeve and Gillespie 174 Elastic Floc Model: Hunter and Co-workers 174 Fractal Concept of Flocculation 175 Rheology of Emulsions 176				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8 7.1.9 7.1.10 7.1.10.1 7.1.10.2 7.1.11 7.1.11.1 7.1.11.2 7.2 7.2 7.2.1	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170 Rheology of Sterically Stabilized Dispersions 171 Rheology of Flocculated Suspensions 171 Weakly Flocculated Suspensions 172 Strongly Flocculated (Coagulated) Suspensions 173 Analysis of the Flow Curve 174 Impulse Theory: Goodeve and Gillespie 174 Elastic Floc Model: Hunter and Co-workers 174 Fractal Concept of Flocculation 175 Rheology of Emulsions 176 Introduction 176				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8 7.1.9 7.1.10 7.1.10.1 7.1.10.2 7.1.11 7.1.11.1 7.1.11.2 7.2 7.2 7.2.1 7.2.2	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170 Rheology of Sterically Stabilized Dispersions 171 Rheology of Flocculated Suspensions 171 Weakly Flocculated Suspensions 172 Strongly Flocculated (Coagulated) Suspensions 173 Analysis of the Flow Curve 174 Impulse Theory: Goodeve and Gillespie 174 Elastic Floc Model: Hunter and Co-workers 174 Fractal Concept of Flocculation 175 Rheology of Emulsions 176 Introduction 176 Interfacial Rheology 176				
7.1.1 7.1.2 7.1.3 7.1.4 7.1.5 7.1.6 7.1.7 7.1.8 7.1.9 7.1.10 7.1.10.1 7.1.10.2 7.1.11 7.1.11.1 7.1.11.2 7.2 7.2 7.2.1 7.2.2	Rheology of Suspensions 165 Introduction 165 The Einstein Equation 166 Rheology of Concentrated Suspensions 166 Rheology of Hard-Sphere Suspensions 167 Analysis of the Viscosity-Volume Fraction Curve 169 Rheology of Systems with 'Soft' or Electrostatic Interaction 169 Viscoelastic Behavior of Electrostatically Stabilized Suspensions 170 Rheology of Sterically Stabilized Dispersions 171 Rheology of Flocculated Suspensions 171 Weakly Flocculated Suspensions 172 Strongly Flocculated (Coagulated) Suspensions 173 Analysis of the Flow Curve 174 Impulse Theory: Goodeve and Gillespie 174 Elastic Floc Model: Hunter and Co-workers 174 Fractal Concept of Flocculation 175 Rheology of Emulsions 176 Interfacial Rheology 176 Interfacial Tension and Surface Pressure 176				

XII C	ontents
-------	---------

7.2.2.3	Measurement of Interfacial Viscosity 177
7.2.3	Interfacial Dilational Elasticity 178
7.2.4	Interfacial Dilational Viscosity 179
7.2.5	Non-Newtonian Effects 179
7.2.6	Correlation of Emulsion Stability with Interfacial Rheology 179
7.2.6.1	Mixed Surfactant Films 179
7.2.6.2	Protein Films 180
7.2.7	Bulk Rheology of Emulsions 181
7.2.8	Experimental η_r – ϕ Curves 183
7.2.8.1	Influence of Droplet Deformability 184
7.2.9	Viscoelastic Properties of Concentrated Emulsions 184
7.3	Rheology of Suspoemulsions of Polystyrene Latex and Isoparaffinic Oil Stabilized with Synperonic PE (PEO-PPO-PEO A-B-A Block Copolymer) 186
7.3.1	Model Systems of Polystyrene Latex with Grafted PEO Chains and
	Hexadecane Emulsions 188
	References 190
8	Rheology Modifiers, Thickeners and Gels 193
8.1	Introduction 193
8.2	Classification of Thickeners and Gels 193
8.3	Definition of a 'Gel' 193
8.4	Rheological Behavior of a 'Gel' 194
8.4.1	Stress Relaxation (After Sudden Application of Strain) 194
8.4.2	Constant Stress (Creep) Measurements 196
8.4.3	Dynamic (Oscillatory) Measurements 196
8.5	Classification of Gels 197
8.6	Polymer Gels 198
8.6.1	Physical Gels Obtained by Chain Overlap 198
8.6.2	Gels Produced by Associative Thickeners 199
8.6.3	Cross-linked Gels (Chemical Gels) 204
8.7	Particulate Gels 205
8.7.1	Aqueous Clay Gels 205
8.7.2	Organo-clays (Bentones) 207
8.7.3	Oxide Gels 207
8.7.4	Gels Produced Using Particulate Solids and High Molecular Weight
	Polymers 208
	References 209
9	Rheology of Paints 211
9.1	Introduction 211
9.2	Experimental Techniques for Studying Paint Rheology 214
9.2.1	Experimental Methods for Quality Control 214
9.2.2	Measurement of Film Flow-out (Leveling and Sagging) 215
9.2.2.1	Impact Method (Bouncing Ball) 215

9.2.2.2	Impedance Method at High Frequency 216				
9.2.3	Rheological Techniques for Research and Development of a Paint				
	System 217				
9.2.4	Steady-state Shear Stress–Shear Rate Measurements 217				
9.2.4.1	Power Law Fluid Model 218				
9.2.4.2	Herschel-Bulkley General Model 218				
9.2.4.3	Casson Model 219				
9.2.4.4	Cross Equation 219				
9.2.5	Thixotropy 220				
9.2.5.1	Transient Methods for Studying Paint Rheology 222				
9.2.6	Analysis of Creep Curves 223				
9.2.6.1	Viscoelastic Liquid 223				
9.2.6.2	Viscoelastic Solid 223				
9.2.6.3	Berger Model (Maxwell + Kelvin) 223				
9.2.6.4	Creep Procedure 223				
9.2.7	Dynamic (Oscillatory) Techniques 225				
9.2.7.1	Analysis of Oscillatory Response for a Viscoelastic System 225				
9.2.7.2	Strain Sweep 226				
9.2.7.3	Oscillatory Sweep 227				
9.2.7.4	Cohesive Energy Density, E _c 227				
9.2.8	Normal Force 227				
9.2.9	Extensional (Elongational) Viscosity 228				
9.3	Application of Rheological Techniques to Paint Formulations 228				
9.3.1	Aging 229				
9.3.2	Temperature 230				
9.3.3	Dispersion and Ingredients 230				
9.3.4	Effect of Surface-active Agents and Dispersants 232				
9.3.5	Grinding and Mixing 233				
9.4	Application of Rheology for Paint Evaluation 234				
9.4.1	Flow in Pipes 236				
9.5	Examples of the Flow Properties of Some Commercial Paints 238				
	References 241				

Index 243