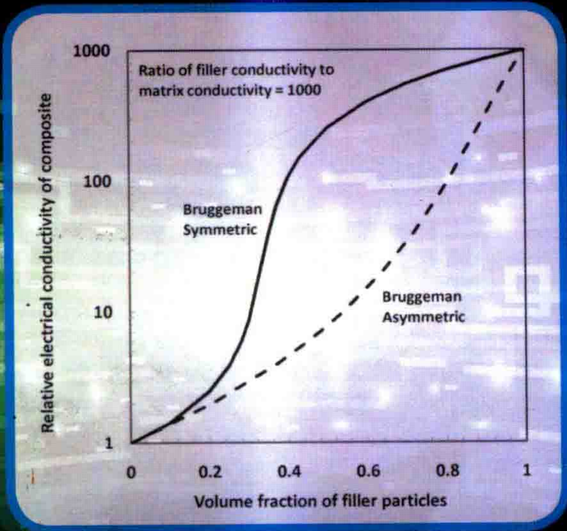
surfactant science series volume **158**

# Electromagnetic, Mechanical, and Transport Properties of Composite Materials




RAJINDER PAL

CRC Press
Taylor & Francis Group

# Electromagnetic, Mechanical, and Transport Properties of Composite Materials

**RAJINDER PAL**
Professor of Chemical Engineering
University of Waterloo
Ontario, Canada

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742



Printed on acid-free paper
Version Date: 20140624

International Standard Book Number-13: 978-1-4200-8921-9 (Hardback)



**Library of Congress Cataloging-in-Publication Data**

Pal, Rajinder.
Electromagnetic, thermal, and mass transport properties of dispersions and composites / Rajinder Pal.
pages cm. -- (Surfactant science series ; 158)
"A CRC title."
Includes bibliographical references and index.
ISBN 978-1-4200-8921-9 (hardcover : alk. paper) 1. Composite materials. 2. Composite materials--Electric properties. 3. Composite materials--Thermal properties. 4. Metallic composites--Electric properties. 5. Metallic composites--Thermal properties. 6. Mechanical alloying. I. Title.

TA418.9.C6P345 2015
620.1'189--dc23 2014024208

**Visit the Taylor & Francis Web site at**
**http://www.taylorandfrancis.com**

**and the CRC Press Web site at**
**http://www.crcpress.com**

# Electromagnetic, Mechanical, and Transport Properties of Composite Materials

# SURFACTANT SCIENCE SERIES

FOUNDING EDITOR
MARTIN J. SCHICK
*1918–1998*

SERIES EDITOR
ARTHUR T. HUBBARD
*Santa Barbara Science Project*
*Santa Barbara, California*

1. Nonionic Surfactants, *edited by Martin J. Schick* (see also Volumes 19, 23, and 60)
2. Solvent Properties of Surfactant Solutions, *edited by Kozo Shinoda* (see Volume 55)
3. Surfactant Biodegradation, *R. D. Swisher* (see Volume 18)
4. Cationic Surfactants, *edited by Eric Jungermann* (see also Volumes 34, 37, and 53)
5. Detergency: Theory and Test Methods (in three parts), *edited by W. G. Cutler and R. C. Davis* (see also Volume 20)
6. Emulsions and Emulsion Technology (in three parts), *edited by Kenneth J. Lissant*
7. Anionic Surfactants (in two parts), *edited by Warner M. Linfield* (see Volume 56)
8. Anionic Surfactants: Chemical Analysis, *edited by John Cross*
9. Stabilization of Colloidal Dispersions by Polymer Adsorption, *Tatsuo Sato and Richard Ruch*
10. Anionic Surfactants: Biochemistry, Toxicology, Dermatology, *edited by Christian Gloxhuber* (see Volume 43)
11. Anionic Surfactants: Physical Chemistry of Surfactant Action, *edited by E. H. Lucassen-Reynders*
12. Amphoteric Surfactants, *edited by B. R. Bluestein and Clifford L. Hilton* (see Volume 59)
13. Demulsification: Industrial Applications, *Kenneth J. Lissant*
14. Surfactants in Textile Processing, *Arved Datyner*
15. Electrical Phenomena at Interfaces: Fundamentals, Measurements, and Applications, *edited by Ayao Kitahara and Akira Watanabe*
16. Surfactants in Cosmetics, *edited by Martin M. Rieger* (see Volume 68)
17. Interfacial Phenomena: Equilibrium and Dynamic Effects, *Clarence A. Miller and P. Neogi*
18. Surfactant Biodegradation: Second Edition, Revised and Expanded, *R. D. Swisher*
19. Nonionic Surfactants: Chemical Analysis, *edited by John Cross*
20. Detergency: Theory and Technology, *edited by W. Gale Cutler and Erik Kissa*
21. Interfacial Phenomena in Apolar Media, *edited by Hans-Friedrich Eicke and Geoffrey D. Parfitt*
22. Surfactant Solutions: New Methods of Investigation, *edited by Raoul Zana*
23. Nonionic Surfactants: Physical Chemistry, *edited by Martin J. Schick*
24. Microemulsion Systems, *edited by Henri L. Rosano and Marc Clausse*
25. Biosurfactants and Biotechnology, *edited by Naim Kosaric, W. L. Cairns, and Neil C. C. Gray*
26. Surfactants in Emerging Technologies, *edited by Milton J. Rosen*

27. Reagents in Mineral Technology, *edited by P. Somasundaran and Brij M. Moudgil*
28. Surfactants in Chemical/Process Engineering, *edited by Darsh T. Wasan, Martin E. Ginn, and Dinesh O. Shah*
29. Thin Liquid Films, *edited by I. B. Ivanov*
30. Microemulsions and Related Systems: Formulation, Solvency, and Physical Properties, *edited by Maurice Bourrel and Robert S. Schechter*
31. Crystallization and Polymorphism of Fats and Fatty Acids, *edited by Nissim Garti and Kiyotaka Sato*
32. Interfacial Phenomena in Coal Technology, *edited by Gregory D. Botsaris and Yuli M. Glazman*
33. Surfactant-Based Separation Processes, *edited by John F. Scamehorn and Jeffrey H. Harwell*
34. Cationic Surfactants: Organic Chemistry, *edited by James M. Richmond*
35. Alkylene Oxides and Their Polymers, *F. E. Bailey, Jr., and Joseph V. Koleske*
36. Interfacial Phenomena in Petroleum Recovery, *edited by Norman R. Morrow*
37. Cationic Surfactants: Physical Chemistry, *edited by Donn N. Rubingh and Paul M. Holland*
38. Kinetics and Catalysis in Microheterogeneous Systems, *edited by M. Grätzel and K. Kalyanasundaram*
39. Interfacial Phenomena in Biological Systems, *edited by Max Bender*
40. Analysis of Surfactants, *Thomas M. Schmitt* (see Volume 96)
41. Light Scattering by Liquid Surfaces and Complementary Techniques, *edited by Dominique Langevin*
42. Polymeric Surfactants, *Irja Piirma*
43. Anionic Surfactants: Biochemistry, Toxicology, Dermatology, Second Edition, Revised and Expanded, *edited by Christian Gloxhuber and Klaus Künstler*
44. Organized Solutions: Surfactants in Science and Technology, *edited by Stig E. Friberg and Björn Lindman*
45. Defoaming: Theory and Industrial Applications, *edited by P. R. Garrett*
46. Mixed Surfactant Systems, *edited by Keizo Ogino and Masahiko Abe*
47. Coagulation and Flocculation: Theory and Applications, *edited by Bohuslav Dobiás*
48. Biosurfactants: Production Properties Applications, *edited by Naim Kosaric*
49. Wettability, *edited by John C. Berg*
50. Fluorinated Surfactants: Synthesis Properties Applications, *Erik Kissa*
51. Surface and Colloid Chemistry in Advanced Ceramics Processing, *edited by Robert J. Pugh and Lennart Bergström*
52. Technological Applications of Dispersions, *edited by Robert B. McKay*
53. Cationic Surfactants: Analytical and Biological Evaluation, *edited by John Cross and Edward J. Singer*
54. Surfactants in Agrochemicals, *Tharwat F. Tadros*
55. Solubilization in Surfactant Aggregates, *edited by Sherril D. Christian and John F. Scamehorn*
56. Anionic Surfactants: Organic Chemistry, *edited by Helmut W. Stache*
57. Foams: Theory, Measurements, and Applications, *edited by Robert K. Prud'homme and Saad A. Khan*

58. The Preparation of Dispersions in Liquids, *H. N. Stein*
59. Amphoteric Surfactants: Second Edition, *edited by Eric G. Lomax*
60. Nonionic Surfactants: Polyoxyalkylene Block Copolymers, *edited by Vaughn M. Nace*
61. Emulsions and Emulsion Stability, *edited by Johan Sjöblom*
62. Vesicles, *edited by Morton Rosoff*
63. Applied Surface Thermodynamics, *edited by A. W. Neumann and Jan K. Spelt*
64. Surfactants in Solution, *edited by Arun K. Chattopadhyay and K. L. Mittal*
65. Detergents in the Environment, *edited by Milan Johann Schwuger*
66. Industrial Applications of Microemulsions, *edited by Conxita Solans and Hironobu Kunieda*
67. Liquid Detergents, *edited by Kuo-Yann Lai*
68. Surfactants in Cosmetics: Second Edition, Revised and Expanded, *edited by Martin M. Rieger and Linda D. Rhein*
69. Enzymes in Detergency, *edited by Jan H. van Ee, Onno Misset, and Erik J. Baas*
70. Structure-Performance Relationships in Surfactants, *edited by Kunio Esumi and Minoru Ueno*
71. Powdered Detergents, *edited by Michael S. Showell*
72. Nonionic Surfactants: Organic Chemistry, *edited by Nico M. van Os*
73. Anionic Surfactants: Analytical Chemistry, Second Edition, Revised and Expanded, *edited by John Cross*
74. Novel Surfactants: Preparation, Applications, and Biodegradability, *edited by Krister Holmberg*
75. Biopolymers at Interfaces, *edited by Martin Malmsten*
76. Electrical Phenomena at Interfaces: Fundamentals, Measurements, and Applications, Second Edition, Revised and Expanded, *edited by Hiroyuki Ohshima and Kunio Furusawa*
77. Polymer-Surfactant Systems, *edited by Jan C. T. Kwak*
78. Surfaces of Nanoparticles and Porous Materials, *edited by James A. Schwarz and Cristian I. Contescu*
79. Surface Chemistry and Electrochemistry of Membranes, *edited by Torben Smith Sørensen*
80. Interfacial Phenomena in Chromatography, *edited by Emile Pefferkorn*
81. Solid–Liquid Dispersions, *Bohuslav Dobiás, Xueping Qiu, and Wolfgang von Rybinski*
82. Handbook of Detergents, editor in chief: Uri Zoller Part A: Properties, *edited by Guy Broze*
83. Modern Characterization Methods of Surfactant Systems, *edited by Bernard P. Binks*
84. Dispersions: Characterization, Testing, and Measurement, *Erik Kissa*
85. Interfacial Forces and Fields: Theory and Applications, *edited by Jyh-Ping Hsu*
86. Silicone Surfactants, *edited by Randal M. Hill*

87. Surface Characterization Methods: Principles, Techniques, and Applications, *edited by Andrew J. Milling*
88. Interfacial Dynamics, *edited by Nikola Kallay*
89. Computational Methods in Surface and Colloid Science, *edited by Malgorzata Borówko*
90. Adsorption on Silica Surfaces, *edited by Eugène Papirer*
91. Nonionic Surfactants: Alkyl Polyglucosides, *edited by Dieter Balzer and Harald Lüders*
92. Fine Particles: Synthesis, Characterization, and Mechanisms of Growth, *edited by Tadao Sugimoto*
93. Thermal Behavior of Dispersed Systems, *edited by Nissim Garti*
94. Surface Characteristics of Fibers and Textiles, *edited by Christopher M. Pastore and Paul Kiekens*
95. Liquid Interfaces in Chemical, Biological, and Pharmaceutical Applications, *edited by Alexander G. Volkov*
96. Analysis of Surfactants: Second Edition, Revised and Expanded, *Thomas M. Schmitt*
97. Fluorinated Surfactants and Repellents: Second Edition, Revised and Expanded, *Erik Kissa*
98. Detergency of Specialty Surfactants, *edited by Floyd E. Friedli*
99. Physical Chemistry of Polyelectrolytes, *edited by Tsetska Radeva*
100. Reactions and Synthesis in Surfactant Systems, *edited by John Texter*
101. Protein-Based Surfactants: Synthesis, Physicochemical Properties, and Applications, *edited by Ifendu A. Nnanna and Jiding Xia*
102. Chemical Properties of Material Surfaces, *Marek Kosmulski*
103. Oxide Surfaces, *edited by James A. Wingrave*
104. Polymers in Particulate Systems: Properties and Applications, *edited by Vincent A. Hackley, P. Somasundaran, and Jennifer A. Lewis*
105. Colloid and Surface Properties of Clays and Related Minerals, *Rossman F. Giese and Carel J. van Oss*
106. Interfacial Electrokinetics and Electrophoresis, *edited by Ángel V. Delgado*
107. Adsorption: Theory, Modeling, and Analysis, *edited by József Tóth*
108. Interfacial Applications in Environmental Engineering, *edited by Mark A. Keane*
109. Adsorption and Aggregation of Surfactants in Solution, *edited by K. L. Mittal and Dinesh O. Shah*
110. Biopolymers at Interfaces: Second Edition, Revised and Expanded, *edited by Martin Malmsten*
111. Biomolecular Films: Design, Function, and Applications, *edited by James F. Rusling*
112. Structure–Performance Relationships in Surfactants: Second Edition, Revised and Expanded, *edited by Kunio Esumi and Minoru Ueno*
113. Liquid Interfacial Systems: Oscillations and Instability, *Rudolph V. Birikh, Vladimir A. Briskman, Manuel G. Velarde, and Jean-Claude Legros*
114. Novel Surfactants: Preparation, Applications, and Biodegradability: Second Edition, Revised and Expanded, *edited by Krister Holmberg*

115. Colloidal Polymers: Synthesis and Characterization, *edited by Abdelhamid Elaissari*
116. Colloidal Biomolecules, Biomaterials, and Biomedical Applications, *edited by Abdelhamid Elaissari*
117. Gemini Surfactants: Synthesis, Interfacial and Solution-Phase Behavior, and Applications, *edited by Raoul Zana and Jiding Xia*
118. Colloidal Science of Flotation, *Anh V. Nguyen and Hans Joachim Schulze*
119. Surface and Interfacial Tension: Measurement, Theory, and Applications, *edited by Stanley Hartland*
120. Microporous Media: Synthesis, Properties, and Modeling, *Freddy Romm*
121. Handbook of Detergents, editor in chief: Uri Zoller, Part B: Environmental Impact, *edited by Uri Zoller*
122. Luminous Chemical Vapor Deposition and Interface Engineering, *Hirotsugu Yasuda*
123. Handbook of Detergents, editor in chief: Uri Zoller, Part C: Analysis, *edited by Heinrich Waldhoff and Rüdiger Spilker*
124. Mixed Surfactant Systems: Second Edition, Revised and Expanded, *edited by Masahiko Abe and John F. Scamehorn*
125. Dynamics of Surfactant Self-Assemblies: Micelles, Microemulsions, Vesicles and Lyotropic Phases, *edited by Raoul Zana*
126. Coagulation and Flocculation: Second Edition, *edited by Hansjoachim Stechemesser and Bohulav Dobiás*
127. Bicontinuous Liquid Crystals, *edited by Matthew L. Lynch and Patrick T. Spicer*
128. Handbook of Detergents, editor in chief: Uri Zoller, Part D: Formulation, *edited by Michael S. Showell*
129. Liquid Detergents: Second Edition, *edited by Kuo-Yann Lai*
130. Finely Dispersed Particles: Micro-, Nano-, and Atto-Engineering, *edited by Aleksandar M. Spasic and Jyh-Ping Hsu*
131. Colloidal Silica: Fundamentals and Applications, *edited by Horacio E. Bergna and William O. Roberts*
132. Emulsions and Emulsion Stability, Second Edition, *edited by Johan Sjöblom*
133. Micellar Catalysis, *Mohammad Niyaz Khan*
134. Molecular and Colloidal Electro-Optics, *Stoyl P. Stoylov and Maria V. Stoimenova*
135. Surfactants in Personal Care Products and Decorative Cosmetics, Third Edition, *edited by Linda D. Rhein, Mitchell Schlossman, Anthony O'Lenick, and P. Somasundaran*
136. Rheology of Particulate Dispersions and Composites, *Rajinder Pal*
137. Powders and Fibers: Interfacial Science and Applications, *edited by Michel Nardin and Eugène Papirer*
138. Wetting and Spreading Dynamics, *edited by Victor Starov, Manuel G. Velarde, and Clayton Radke*
139. Interfacial Phenomena: Equilibrium and Dynamic Effects, Second Edition, *edited by Clarence A. Miller and P. Neogi*

140. Giant Micelles: Properties and Applications, *edited by Raoul Zana and Eric W. Kaler*
141. Handbook of Detergents, editor in chief: Uri Zoller, Part E: Applications, *edited by Uri Zoller*
142. Handbook of Detergents, editor in chief: Uri Zoller, Part F: Production, *edited by Uri Zoller and co-edited by Paul Sosis*
143. Sugar-Based Surfactants: Fundamentals and Applications, *edited by Cristóbal Carnero Ruiz*
144. Microemulsions: Properties and Applications, *edited by Monzer Fanun*
145. Surface Charging and Points of Zero Charge, *Marek Kosmulski*
146. Structure and Functional Properties of Colloidal Systems, *edited by Roque Hidalgo-Álvarez*
147. Nanoscience: Colloidal and Interfacial Aspects, *edited by Victor M. Starov*
148. Interfacial Chemistry of Rocks and Soils, *Noémi M. Nagy and József Kónya*
149. Electrocatalysis: Computational, Experimental, and Industrial Aspects, *edited by Carlos Fernando Zinola*
150. Colloids in Drug Delivery, *edited by Monzer Fanun*
151. Applied Surface Thermodynamics: Second Edition, *edited by A. W. Neumann, Robert David, and Yi Y. Zuo*
152. Colloids in Biotechnology, *edited by Monzer Fanun*
153. Electrokinetic Particle Transport in Micro/Nano-fluidics: Direct Numerical Simulation Analysis, *Shizhi Qian and Ye Ai*
154. Nuclear Magnetic Resonance Studies of Interfacial Phenomena, *Vladimir M. Gun'ko and Vladimir V. Turov*
155. The Science of Defoaming: Theory, Experiment and Applications, *Peter R. Garrett*
156. Soil Colloids: Properties and Ion Binding, *Fernando V. Molina*
157. Surface Tension and Related Thermodynamic Quantities of Aqueous Electrolyte Solutions, *Norihiro Matubayasi*
158. Electromagnetic, Mechanical, and Transport Properties of Composite Materials, *Rajinder Pal*

*To the memory of my parents,*
*Smt Karma-Bhari and Shri Khushal Chand*

# Preface

Composite materials are blends of two or more materials of different physical properties. The individual materials are immiscible with each other and exist as distinct phases. Thus, composite materials are multiphase materials consisting of two or more phases. Different materials are mixed together with the purpose of generating superior materials having properties better than those of the individual materials. Composite materials are a rapidly growing class of materials, with applications in industries such as plastics, automotive, electronic, packaging, aircraft, space, sports, and the biomedical field.

In the design, processing, and applications of composite materials, a thorough understanding of the physical properties is required. It is important to be able to predict the variations of the electromagnetic (electrical conductivity, dielectric constant, and magnetic permeability), mechanical; thermal (thermal conductivity and coefficient of thermal expansion), and mass transport properties of composite materials with the kind, shape, and concentration of filler materials. The filler material may consist of equiaxed particles ranging anywhere from nanometers to microns in size, discontinuous short fibers or whiskers, small disk- or plate-shaped particles/flakes, or core-and-shell type of complex particles.

A number of excellent books are available on composite materials, but for the most part, they are restricted to classification, applications, and manufacturing of composite materials along with the characterization of mechanical properties. The electromagnetic, thermal, and mass transport properties of composite materials have generally received little attention as compared with the mechanical properties even though they are equally important from a practical point of view.

The study of electrical, dielectric, and magnetic properties of composite materials can reveal valuable information regarding the morphology and composition of such systems. For example, the dielectric probes could be used to probe the microstructure and to estimate the filler content of composites, especially when the dielectric constants of the individual materials are significantly different from each other. The electrical properties of composites are important in the design of plastics used in the electronics industry. Pure plastics tend to pick up electrostatic charges, especially under low-humidity conditions. When earthed, the (charged) plastics discharge and, in the process, damage electronic circuitry and equipment. To overcome the problems associated with electrostatic charge of plastics, electrically conducting filler particles (such as carbon black) are incorporated into the plastic matrix. The incorporation of electrically conducting filler particles into the plastic matrix imparts electrical conductivity to the plastic system, and as a consequence, the buildup of static charge is avoided. The magnetic properties of composite materials are of interest in many industrial applications involving electrical and electronic instruments, electrical power generators and transformers, electric motors, radio, television, telephones, computers, audio and video equipment, etc.

The thermal properties of composite materials are important in many practical applications. For example, knowledge of the coefficient of thermal expansion (CTE) of composites is required in calculating dimensional changes and buildup of internal stresses when composites are subjected to temperature changes. In designing a composite material, it is often necessary to match the CTE of different components. The other very important thermal property of composite materials is their thermal conductivity. In the electronics industry, the packaging material used to encapsulate electronic devices must have a high thermal conductivity in order to dissipate the heat generated by the device as rapidly and effectively as possible. Particulate composites consisting of polymer matrix and heat-conducting fillers are used for this purpose. Polymers filled with heat-conducting fillers provide the required thermal conductivity while maintaining the electrical insulation properties of the polymers. It has been recently discovered that the addition of a small amount of nanoparticles (such as carbon nanotubes and copper nanoparticles) can greatly improve the thermal conductivity of polymers.

The mass transport properties of composite materials are important in the design and application of composite membranes. Composite membranes are extensively used in the separation of gas mixtures. In the packaging industry, composite membranes are used as barrier films.

The aim of this book is to provide a systematic and comprehensive coverage of the electromagnetic, mechanical, thermal, and mass transport properties of composite materials. Throughout the book, the analogy between various properties is emphasized. The book draws heavily on the work of the author on physical properties of composite materials.

The first chapter of the book discusses the important applications of composite materials and the relevance of electromagnetic, mechanical, and transport properties. The book is then organized in three parts: Electromagnetic properties of composites (Sections I and II), Mechanical properties of composites (Section III), and Transport properties of composites (Sections IV and V). Section I, titled Static electromagnetic properties of composites, deals with the electromagnetic properties of composite materials subjected to time-invariant electric and magnetic fields. It consists of three chapters. Chapter 2 describes the electrical conductivity of composites, Chapter 3 the dielectric properties, and Chapter 4 describes the magnetic properties of composites. Section II, titled General treatment of electromagnetic phenomena in composites, deals with the dynamic electromagnetic properties of composite materials subjected to time-varying electric and magnetic fields. This section consists of two chapters. Chapter 5 deals with the fundamental aspects of electromagnetic phenomena. The general laws of electromagnetism (Maxwell equations) and the generalized conductivity principle are discussed. Chapter 6 describes the complex electromagnetic properties of composites. The frequency dependence of electromagnetic properties of composite materials is also discussed in details. Section III (Mechanical properties of composites) consists of seven chapters. Chapter 7 describes the mechanical properties of *dilute* particulate-filled composites. The mechanical properties of *concentrated* composites are described in Chapters 8 through 11. The influence of interfacial and interphase effects on the mechanical properties of composites is discussed in Chapter 12. The viscoelastic behavior of composite materials is covered in Chapter 13. Section IV, titled Heat transfer in composites, consists of seven chapters. Chapters 14 and 15 cover the fundamental aspects of heat transfer. Chapters 16 and 17 describe the thermal conductivity of particulate composites. The influence of interfacial contact resistance on the thermal conductivity of composites is covered in Chapter 18. The thermal diffusivity and coefficient of thermal expansion of composites are dealt with in Chapter 19. The radiative heat transfer properties of composite materials are described in Chapter 20. Section V, titled Mass transfer in composites, consists of Chapters 21 through 24. Chapter 21 covers the fundamentals of diffusion mass transfer. The diffusion mass transfer in composite membranes is described in Chapter 22. Chapter 23 deals with the fundamentals of convective mass transfer, and Chapter 24 covers convective mass transfer in composite materials.

I hope that scientists, engineers, and students from a broad range of fields will find this book an attractive and comprehensive source of information on the subject. The book provides both an introduction to the subject for newcomers and sufficient in-depth coverage for those involved in research related to the electromagnetic, mechanical, and transport phenomena in composite materials.

Finally, I would like to thank my wife Archana and my children Anuva and Arnav for their love and constant support.

**Rajinder Pal**

# Author

**Rajinder Pal** is a Professor of Chemical Engineering at the University of Waterloo, Ontario, Canada. He received the BTech degree (1981) in Chemical Engineering from the Indian Institute of Technology, Kanpur, India, and a PhD degree (1987) in Chemical Engineering from the University of Waterloo. The author of more than 120 refereed journal publications and a book in the areas of rheological, mechanical, electromagnetic, and transport properties of dispersed systems (emulsions, suspensions, foams, particulate composites, and composite membranes), Dr. Pal is a fellow of the Chemical Institute of Canada. In recognition of his distinguished contributions in chemical engineering before the age of 40, he received the Syncrude Canada Innovation Award in 1998 from the Canadian Society for Chemical Engineering. In 2001, he received the Teaching Excellence Award of the Faculty of Engineering, University of Waterloo. Dr. Pal served as Associate Editor of the *Canadian Journal of Chemical Engineering* from 1992 to 2004. He is a registered Professional Engineer in the province of Ontario, Canada.

# Contents

# SECTION II Electromagnetic Properties of Composites: General Treatment of Electromagnetic Phenomena in Composites



# SECTION III Mechanical Properties of Composites