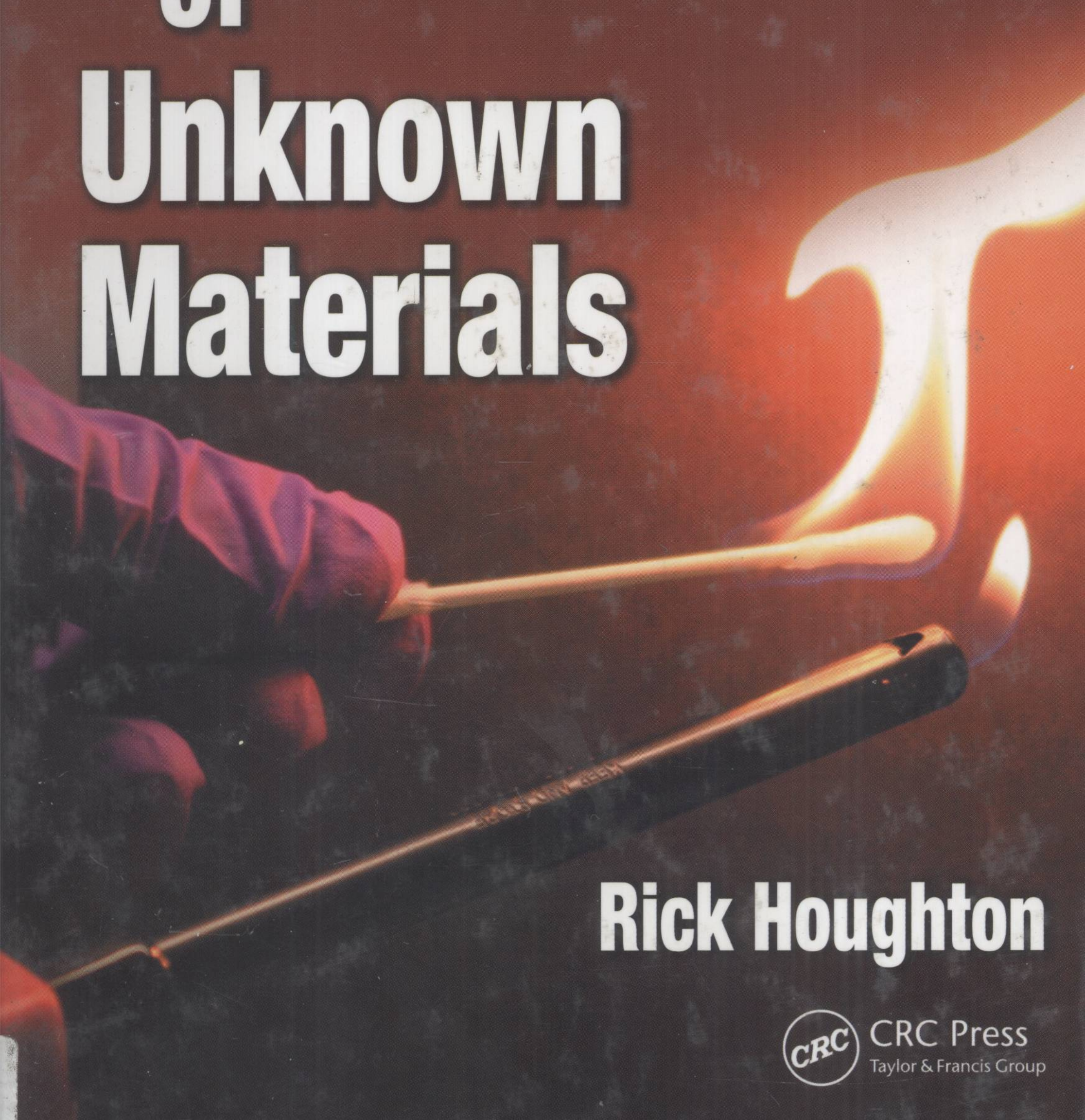
Emergency Characterization of Unknown Materials



Rick Houghton

CRC Press
Taylor & Francis Group

W. Ehlers • J. Bluhm (Eds.)

Porous Media

Theory, Experiments and Numerical Applications

With 152 Figures

Springer

Prof. Dr.-Ing. Wolfgang Ehlers
Universität Stuttgart
Institut für Mechanik (Bauwesen)
Lehrstuhl II
Pfaffenwaldring 7
D - 70569 Stuttgart
e-mail: ehlers@mechbau.uni-stuttgart.de

Priv. Doz. Dr.-Ing. Joachim Bluhm
Universität Essen
Institut für Mechanik
Universitätsstr. 15
D - 45141 Essen
e-mail: joachim.bluhm@uni-essen.de

ISBN 3-540-43763-0 Springer-Verlag Berlin Heidelberg New York

Library of Congress Cataloging-in-Publication-Data applied for

Die Deutsche Bibliothek – Cip-Einheitsaufnahme
Porous media : theory, experiments and numerical applications /
W. Ehlers ; J. Bluhm (ed.) - Berlin ; Heidelberg ; New York ;
Barcelona ; Hong Kong ; London ; Milan ; Paris ; Tokyo : Springer, 2002
(Engineering online library)
ISBN 3-540-43763-0

Springer-Verlag Berlin Heidelberg New York
a member of BertelsmannSpringer Science+Business Media GmbH
http://www.springer.de

Typesetting: data delived by editors
Cover design: de'blik, Berlin
Printed on acid free paper SPIN: 10882577 62/3020/M - 5 4 3 2 1 0

Springer

Berlin
Heidelberg
New York
Barcelona
Hong Kong
London
Milan
Paris
Tokyo

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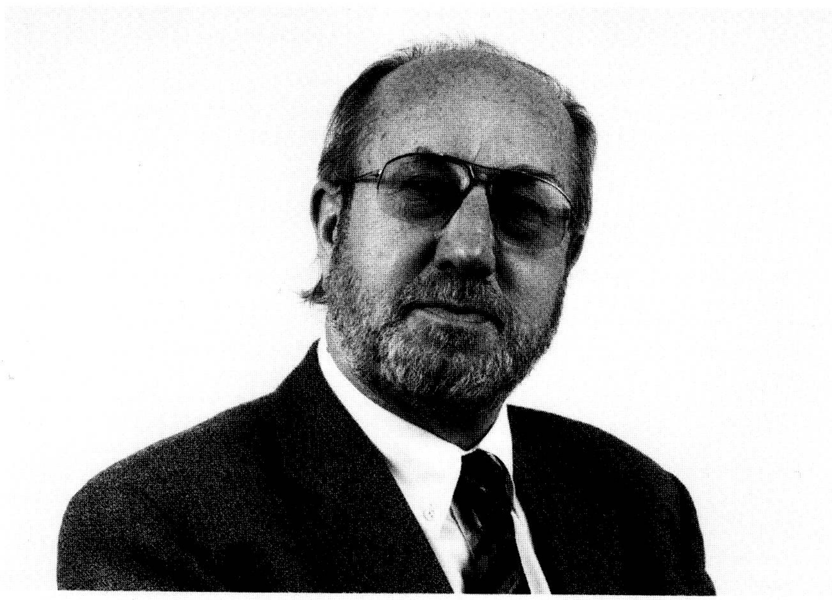

to *Reint de Boer*, our teacher

Preface

The present volume offers a *state-of-the-art* report on the various recent scientific developments in the Theory of Porous Media (TPM) comprehending the basic theoretical concepts in continuum mechanics on porous and multiphasic materials as well as the wide range of experimental and numerical applications. Following this, the volume does not only address the sophisticated reader but also the interested beginner in the area of Porous Media by presenting a collection of articles. These articles written by experts in the field concern the fundamental approaches to multiphasic and porous materials as well as various applications to engineering problems.

In many branches of engineering just as in applied natural sciences like bio- and chemomechanics, one often has to deal with continuum mechanical problems which cannot be uniquely classified within the well-known disciplines of either *"solid mechanics"* or *"fluid mechanics"*. These problems, characterized by the fact that they require a unified treatment of volumetrically coupled solid-fluid aggregates, basically fall into the categories of either mixtures or porous media. Following this, there is a broad variety of problems ranging in this category as for example the investigation of reacting fluid mixtures or solid-fluid suspensions as well as the investigation of the coupled solid deformation and pore-fluid flow behaviour of liquid- and gas-saturated porous solid skeleton materials like geomaterials (soil, rock, concrete, etc.), polymeric and metallic foams or biomaterials (hard and soft tissues, etc). In particular, the reader may be interested in the solution of geotechnical problems like the well-known consolidation problem of soil mechanics, or in applications concerning the exploitation of natural gas and oil reservoirs. Furthermore, the interest may be directed towards the investigation of the deformation of foamed shock absorbers as well as towards biomechanical problems like the investigation of bones, cartilage, intervertebral disks or charged hydrated tissues, etc.

Porous Media generally concern an immiscible mixture of a solid skeleton and a fluid pore content which itself can either be a single fluid, gas or liquid, an immiscible fluid mixture of gas and liquids or a miscible fluid mixture of different reacting aggregates. The basic tool for a successful description of this kind of media in the framework of a macroscopic approach is the well-known Theory of Mixtures. On the other hand, since there is no measure to incorporate any kind of microscopic information in the Theory of Mixtures, it was found convenient to combine the *Theory of Mixtures* with the *Concept of Volume Fractions*. By use of this procedure, basically defining the *Theory of Porous Media*, one obtains an excellent tool for the macroscopic description of general immiscible or miscible multiphasic aggregates, where the volume fractions and the saturations, respectively, are the measures of the local portions of the individual constituents of the overall medium and where, furthermore, all incorporated fields can be understood as the local averages of the corresponding quantities of an underlying microstructure.

It is the goal of the present contribution to exhibit the fundamental concepts of the Theory of Porous Media and to apply these concepts to a variety of interesting problems in engineering and natural sciences. Thus, the first chapter of this volume concerns the foundations of modelling multiphasic materials represented by two articles by the editors, whereas the following chapters include five articles on different aspects of the TPM and eight articles on experiments and numerical applications.

Chapter *I. Foundations* starts with an article on the general description of the basic concepts of the Theory of Porous Media, where, in addition to the standard kinematics of the classical continuum mechanical approach to multiphasic and porous materials, also extended kinematics in the sense of the *Cosserat* brothers are taken into consideration. Apart from these fundamental concepts leading to both the standard and the extended framework of balance relations of multiphasic systems, the article furthermore presents two different constitutive models describing, on the one hand, a simple biphasic material of an elastic solid skeleton which is saturated by a single pore-liquid and, on the other hand, a triphasic material consisting of a micropolar elasto-plastic or elasto-viscoplastic solid skeleton saturated by a binary immiscible pore-content of a pore-liquid and a pore-gas. Furthermore, the basic numerical tools in treating volumetrically coupled solid-fluid aggregates are explained and extended by the application of time- and space-adaptive methods. Finally, the article contains a variety of numerical examples exhibiting the solution of civil engineering problems of geotechnical relevance.

The second article of Chapter I describes a fluid-saturated thermo-elastic porous solid, where the solid and the fluid materials are assumed to undergo different phase temperatures. Apart from the governing balance relations, the article includes a general setting of developing a constitutive theory on the basis of thermodynamical restrictions. In addition, the stress states of the thermo-elastic solid and the non-viscous pore-fluid are discussed in detail.

Chapter *II. Theory of Porous Media* presents several extensions in the general description of porous materials. In particular, this chapter starts with an article by *Stefan Diebels* on micropolar mixture models followed by a paper by *Nina Kirchner* and *Kolumban Hutter* on the elasto-plastic behaviour of granular materials with an additional scalar degree of freedom. Furthermore, the contribution by *Stefan Kowalski* deals with the mechanical aspects on drying of wet porous media, whereas *Renato Lancelotta* studies the coupling between the evolution of a deformable porous medium and the motion of fluids in the connected porosity. In contrast to these articles which are more or less related to engineering problems, the last article of this chapter by *Van C. Mow* et al. concerns a very interesting problem of biomechanical engineering, namely a triphasic paradigm by investigating fixed negative charges modulating mechanical behaviours and electrical signals in articular cartilage under unconfined compression.

Chapter *III. Experiments and Numerical Applications* includes eight articles on various applications of the Theory of Porous Media. In particular, *Harald Cramer* et al. describe a time-adaptive analysis of saturated soil by a discontinuous Galerkin method. The following paper by *Wolfgang Ehlers* et al. concerns a biphasic description of viscoelastic foams by use of an extended Ogden-type formulation. The article by *Jacques Huyghe* et al. exhibits an experimental measurement of electrical conductivity and electro-osmotic permeability of ionised porous media and thus presents the second paper of this volume dealing with biomechanical problems. The following three contributions concern civil engineering problems. The first one written by *Ragnar Larsson* et al. describes the theory and numerics of localization in a fluid-saturated elasto-plastic porous medium followed by an article by *Lorenzo Sanavia* et al. on a geometrical and material non-linear analysis of fully and partially saturated porous media. Finally, the paper by *Martin Schanz* and *Heinz Antes* on waves in a poroelastic half-space proceeds from the *Biot*'s theory, which can be understood as a variation of the Theory of Porous Media. In contrast to the preceding articles which are commonly based on the application of the finite element method, this paper furthermore proceeds from the boundary element analysis. Directing the focus of interest to another topic, the article by *Reem Freij-Ayoub* et al. describes a multicomponent reactive transport applied to ore body genesis and environmental hazards. The final paper of this volume by *D. J. R. Owen* et al. concerns a numerical model and its finite element solution for multiphase flow situations with an interesting application to pulp and paper processing.

The foregoing description clearly exhibits the wide range of applications of the Theory of Porous Media to various problems in the fields of engineering and natural sciences. Making use of the quotations given in the individual contributions, the interested reader is in the position to nearly arbitrarily extend the list of possible topics for an application of the Theory of Porous Media.

Finally, it is the wish of the editors to thank Professor Dr.-Ing. *Reint de Boer*, our scientific teacher, for his valuable contributions to the Theory of Porous Media and, particularly, its historical background. His engagement in this topic gave the research in the field of Porous Media a strong input and effectively promoted the modern approach to porous and multiphasic materials.

Stuttgart and Essen, April 2002

Wolfgang Ehlers
Joachim Bluhm

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Printing: Mercedes-Druck, Berlin
Binding: Buchbinderei Lüderitz & Bauer, Berlin

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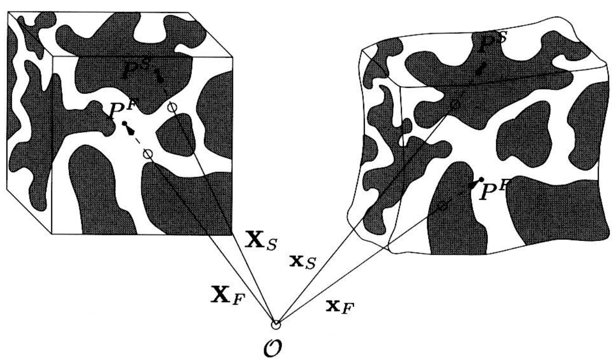

Foundations of multiphasic and porous materials

Wolfgang Ehlers

University of Stuttgart, Institute of Applied Mechanics (CE),
70550 Stuttgart, Germany

Abstract. Miscible multiphasic materials like classical mixtures as well as immiscible materials like saturated and partially saturated porous media can be successfully described on the common basis of the well-founded Theory of Mixtures (TM) or the Theory of Porous Media (TPM). In particular, both the TM and the TPM provide an excellent frame for a macroscopic description of a broad variety of engineering applications and further problems in applied natural sciences. The present article portrays both the standard and the micropolar approaches to multiphasic materials reflecting their mechanical and their thermodynamical frameworks. Including some constitutive models and various illustrative numerical examples, the article can be understood as a reference paper to all the following articles of this volume on theoretical, experimental and numerical investigations in the Theory of Porous Media.

1 Motivation

In many branches of engineering as well as in applied natural sciences, one often has to deal with continuum mechanical problems which cannot be uniquely classified within the well-known disciplines of either *"solid mechanics"* or *"fluid mechanics"*. These problems, characterized by the fact that they require a unified treatment of volumetrically coupled solid-fluid aggregates, basically fall into the categories of either mixtures or porous media. Following this, there is a broad variety of problems ranging in this category as for example the investigation of reacting fluid mixtures or solid-fluid suspensions as well as the investigation of the coupled solid deformation and pore-fluid flow behaviour of liquid- and gas-saturated porous solid skeletons like geomaterials (soil, rock, concrete, etc.), polymeric as well as metallic foams or biomaterials (hard and soft tissues, etc), cf. Figure 1. In particular, one may be interested in the solution of geotechnical applications like the well-known consolidation problem of soil mechanics, or in applications concerning the exploitation of natural gas and oil reservoirs. Furthermore, the interest may be directed towards the investigation of the deformation of foamed shock absorbers or automotive seat cushions as well as towards biomechanical problems like the investigation of bones, cartilage or intervertebral disks, etc.

The treatment of this kind of problems consisting of an immiscible mixture of a solid skeleton and a fluid pore content on the basis of a continuum

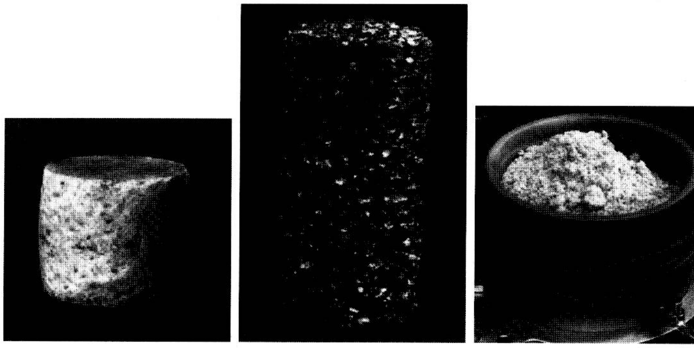

Fig. 1. Three typical porous solid materials.

mechanical method, i. e. within the framework of a macroscopic approach, first of all concerns the question of the necessary or the convenient degree of homogenization. Thus, one has to decide *a priori*, whether (1) each material of the multiphasic aggregate has to be treated by use of a micromechanical approach on its own domain as a single body where, additionally, the interaction mechanisms at the internal interfaces between the individual materials have to be taken into account carefully, or if one (2) wants to proceed from homogenization methods where the real microstructure is statistically smeared out through the considered domain on the basis of a real or a virtual averaging process. Both procedures are based on a considerable scientific tradition and are characterized by certain advantages and disadvantages.

The advantage of the micromechanical procedure lies, on the one hand, in the fact that each individual aggregate can be described on the basis of its own motion (cf. Figure 2) considering the usually known information on the constitutive assumptions of single continua mechanics. On the other hand, however, one has to define convenient interaction and contact relations to catch the coupling mechanisms at the internal interfaces. And just this is the basic problem of the first procedure, since the internal geometry of porous solid materials is, apart from some very few industrial products, of an arbitrary and irregular shape which, in general, is and remains completely unknown. Based on this enormous disadvantage of the first procedure, the necessity of using macroscopic strategies is obvious. Proceeding from macroscopic approaches, one has to be aware that the local information on the material behaviour does only reflect the physical properties of the individual aggregates in the sense of a local average. However, in order to obtain local averages as representative statements, one has to require that (a) the subdomains under study, in the sense of a representative elementary volume (REV), must be large enough to allow for a statistical statement and that (b)