CRC

HANDBOOK of PHYSICAL PROPERTIES of ROCKS

Volume II

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Handbook of Physical Properties of Rocks

Volume II

Editor

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PREFACE

The objective of this handbook is to provide an organized compilation of data on rocks and minerals.

"Science is organized knowledge."

Herbert Spencer
(1820—1903)
English philosopher

The handbook is a current guide to physical properties, for easy reference to and comparison of various properties or various types of materials. Its function is to present a reliable data base that has been selected and evaluated, and as comprehensively as reasonable size limitations will permit. The intent is to bridge the gap between individual reports with only specific limited data, and massive assemblies of data which are uncritically presented.

Individual chapters have been prepared by recognized authorities who are among the leaders of their respective specialties. These authors are drawn from leading university, industrial, and government and scientific establishments. An Advisory Board of nationally prominent geoscientists has helped to oversee the handbook development.

The handbook is interdisciplinary in content and approach. A purpose is to provide data for persons in geology, geophysics, geochemistry, petrophysics materials science, or geotechnical engineering, who might be expert in one special topic but who seek information on materials and properties in another topic. This might be for purposes of evaluation, estimates, modelling, prospecting, assessment of hazards, subsurface character, prediction of properties, beginning new projects, and so on. The expert may have sources of reference as a guide in his area, but needs assistance to get started on something new or on a topic in an allied field.

The format is primarily tabular for easy reference and comparability. In addition to tables and listings, there are graphs and descriptions where appropriate. Graphical trends, e. g., how a property varies with a parameter such as mineral composition or temperature or pressure, can be particularly useful when studying rocks. This is because, for some rock properties, the trend may be more reliable and useful than the absolute value of the property at one particular condition.

Rocks are the foundation of our physical world, both literally and figuratively. The importance of them, and of their physical properties, derives from such applications as:

1. They are the material on or in which geotechnical engineers install buildings, dams, tunnels, bridges, underground storage or waste disposal facilities, and a variety of other structures.
2. They contain the natural resources needed by modern industrial society, including oil and gas, coal, groundwater, geothermal energy, and ore deposits of such metals as iron, copper, lead, zinc, and nickel.
3. Their variations in physical properties such as density, magnetization, elastic-wave velocity, and electrical resistivity provide means for remotely determining subsurface geology and structure by the methods of exploration geophysics.
4. They rupture on fault zones to produce earthquakes and transmit the resulting seismic waves for long distances.
5. Laboratory study of them can often reveal the age, origin, and geologic history of rocks and events.

Physical properties of rocks and of their constituent minerals are of concern to geologists, geophysicists, petrophysicists, and geotechnical engineers. Over the past 20 years or so, there has been a great increase in the amount and variety of data available. This was because of the development of new measuring equipment and analytical techniques, the rise of new applications requiring new or more refined data, and the acquisition of rocks from habitats that had been previously inaccessible. The latter include great depths in the continents (down over 10,000 m in sedimentary basins), the continental shelves and seafloors to depths of several hundred meters below the deep seafloor, and the Moon.

Rock properties are of interest for recently developing topics such as deeper drilling for petroleum and other resources, including deep minerals and geothermal energy development; understanding earthquakes and their prospective prediction based on precursory physical changes occurring in the epicentral area; engineering geology; more refined geophysical prospecting of the subsurface using inherent rock properties as well as rock structure; and study of surface geology from satellite remote sensing.

There is also ever-increasing interest in the properties of rocks and minerals because of new or expanded applications in allied fields. For example, materials scientists and solid-state physicists are interested in such physical properties as the magnetic, electrical, and optical character of mineral crystals. Such information has use for magnetic memory devices for computers, for permanent magnets, and for electronics. Construction engineers need better information on rock properties in unconventional sites, e.g., for installing oil-storage tanks on the seafloor, for burying pipelines in permafrost terrain, and for siting major structures in areas of seismic risk.

''Human knowledge is but an accumulation of small facts made by successive generations of (investigators) — the little bits of knowledge and experience carefully treasured up by them growing at length into a mighty pyramid.''

Samuel Smiles
(1812—1904)
Scottish writer

Chapters in Volume I include:

Mineral composition of rocks — Chemical composition and physical characteristics of igneous, sedimentary, and metamorphic rocks, and of pore fluids (including geothermal fluids), economic ores and fuels (including coal, petroleum, oil shale and tar sands, radioactive minerals), and marine sediments. Properties of minerals and crystals, including petrographic characteristics. Composition of the Earth's crust and mantle, and of meteorites and Moon rock.

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Professor of Geology
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El Paso, Texas

Electrical properties of rocks and minerals — Conductivity/resistivity and dielectric constants of minerals and dry rocks. Variation of electrical properties with temperature, pressure, frequency at which measurement is made, and ithology and porosity. Induced polarization. Resistivity of brine and water-bearing rocks. Electrical properties and electric logs of sedimentary rocks, in situ sequences of rocks, and coal, permafrost, and the Earth's interior.

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Spectroscopic properties of rocks and minerals — Interaction of matter with electromagnetic radiation, in the visible and infrared range. Properties of absorption/transmission, reflection and emission, and spectral characteristics of minerals and rocks.

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Volume II will include:

Seismic velocities — Compressional and shear wave velocities for rocks, minerals, marine sediments and water, aggregates and glasses, the Earth's crust and supper mantle (continental and oceanic), glaciers and permafrost. Laboratory and in situ measurements. Variation of velocity with degree of fluid saturation, pressure and temperature.

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and Graduate Program in Geophysics
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Magnetic properties of minerals and rocks — Magnetic and crystalline properties of magnetic minerals. Types of remanent magnetizations. Magnetic properties of rocks: susceptibility, coercive field, Curie temperature, anisotropy, saturation magnetization. Variation with chemical composition, grain size and shape, temperature and pressure.

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Engineering properties of rock — Factors and tests relating to rock appraisal, characterization, and assessment of properties such as strength, hardness, elastic constants, and deformation. Engineering properties, including the effects of pore water pressure.

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Volume III will include:

Mechanical properties (inelastic) — Inelastic mechanical properties of rocks and minerals, emphasizing strength and rheology. Laboratory tests in rock mechanics, stress-strain relations, and effects of pore fluids, time and stress rate, and temperature. Rock friction. Compilation of experimental data.

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Elastic Constants
Thermal Properties
Seismic Attenuation
Radioactivity Properties

Data have been gathered, transcribed, and reproduced here with as much care as possible; in the event of any apparent uncertainty, one should check with the original references as given.

My thanks are extended to all who have contributed to the formulation and execution of this Handbook series. The editorial function at CRC Press was performed by Susan Cubar, Pamela Woodcock, and Cathy Walker. The University of Iowa provided partial summer support in the form of an Old Gold Fellowship to the Editor. Appreciation is due Dr. Richard Moppin, Chairman of Geology at Iowa, for fostering the supportive environment conducive to professional labors of love such as this.

Robert S. Carmichael
1981

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After graduation in 1967, he spent a year at Osaka University in Japan, as a postdoctoral Research Fellow of the Japan Society for Promotion of Science and working in high-pressure geophysics. Upon return, he joined Shell Oil's Research Center in Houston as a research geophysicist in petroleum exploration. Now at the University of Iowa, Dr. Carmichael has research interests in rock properties, exploration geophysics, high-pressure geophysics and magnetics, and earthquakes in the central Midcontinent region.

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Chapter 1

SEISMIC VELOCITIES

Nikolas I. Christensen

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INTRODUCTION

Seismology has provided a wealth of evidence relating to the physical nature of the interior of the Earth. Most seismological studies using earthquakes or reflection and refraction techniques from artificially generated waves present layered models in which velocities and layer thicknesses are tabulated. Many significant results have emerged from these studies including:

1. The broad subdivision of the Earth into crust, mantle, and core
2. The recognition of seismic discontinuities within the core and mantle that are probably related to phase changes
3. The marked difference in overall structure of the oceanic and continental crust

Several intracrustal discontinuities have, in turn, been recognized which differ from one region to another, and as increasing data become available it is apparent that many regions of the Earth's interior are anisotropic and heterogeneous.

The information desired from seismic studies is not ultimately velocity-depth functions, but knowledge of the nature and distribution of materials with depth so we may understand the origin and evolution of the Earth. The velocities of elastic waves in materials for the interpretation of seismic data must be obtained through carefully controlled laboratory experiments which realistically simulate the physical conditions that exist within the Earth's interior.

In addition to being of interest to Earth scientists, velocities are of considerable significance to materials scientists since they yield information important in understanding forces between atoms and ions. Also, since velocities are related to the elastic properties of solids, they are important in describing the mechanical behavior of materials.

For homogeneous isotropic elastic materials, compressional (V_p) and shear (V_s) wave velocities, density (ϱ), and the elastic moduli are related by the following equations:

Bulk Modulus	$K = \varrho(V_p^2 - 4/3\, V_s^2)$
Shear Modulus	$\mu = \varrho V_s^2$
Poisson's Ratio	$\sigma = \dfrac{(r^2 - 2)}{2(r^2 - 1)}, \quad r = V_p/V_s$
Young's Modulus	$E = 2\mu(1 + \sigma)$
Compressional Wave Velocity	$V_p = \sqrt{[K + (4/3)\mu]/\varrho}$
Shear Wave Velocity	$V_s = \sqrt{\mu/\varrho}$

Laboratory studies of velocities in materials generally fall into three categories: (1) measurements of velocities in naturally occurring materials such as rocks, (2) studies of hot-pressed polycrystalline aggregates, and (3) velocity measurements in single crystals. The velocities in rocks and hot-pressed aggregates are commonly affected by porosity. Values useful for the interpretation of field measurements, except in near-surface studies, are obtained only after porosity has been reduced by application of a few kilobars pressure. Measurements of velocities in single crystals are useful in the interpretation of seismic anisotropy resulting from preferred mineral orientation. In addition, if the elastic constants have been completely determined it is possible to estimate the velocities of quasi-isotropic aggregates of single crystals.

The prediction of velocities of a quasi-isotropic rock containing a large number of randomly oriented, highly anisotropic crystals, from single-crystal data is complicated in many aspects. In theory, it is difficult to compromise between assumptions of uniform local strain and uniform local stress. Voigt[1] assumed that strain is uniform throughout the rock and averaged over solid angles the elastic constants (C_{ij}), whereas Reuss[2] assumed that uniform local stress was operative and averaged the elastic compliances (S_{ij}) over all directions. The appropriate relationships for the bulk moduli and shear moduli according to the two theories are as follows:

Voigt's Moduli

$$9K_v = (C_{11} + C_{22} + C_{33}) + 2(C_{12} + C_{23} + C_{31})$$

$$15\mu_v = (C_{11} + C_{22} + C_{33}) - (C_{12} + C_{23} + C_{31}) + 3(C_{44} + C_{55} + C_{66})$$

Reuss's Moduli

$$1/K_r = (S_{11} + S_{22} + S_{33}) + 2(S_{12} + S_{23} + S_{31})$$

$$15/\mu_r = 4(S_{11} + S_{22} + S_{33}) - 4(S_{12} + S_{23} + S_{31}) + 3(S_{44} + S_{55} + S_{66})$$

Calculated compressional and shear wave velocities for quasi-isotropic monomineralic rocks are obtained from the relationships $\varrho V_p^2 = K + 4\mu/3$ and $\varrho V_s^2 = \mu$ where ϱ is the density of the mineral.

Voigt's and Reuss's velocity averages frequently show considerable variance especially for the silicate minerals of low symmetry. Hill[3] has shown theoretically that the true values lie between the Voigt and Reuss Moduli and the Hill average is commonly taken as the mean of the Voigt and Reuss values.

The accuracies of seismic structure within the Earth depend to a large extent on the combination of field and analytical techniques used to identify the velocities and probably vary between 3 and 10% for most models. The accuracies of laboratory velocities in materials also depend on the specific technique employed, varying from 0.5% to 3% for the pulse-transmission method commonly used for rocks to approximately 0.01% with interferometric methods. The laboratory techniques typically use frequencies much higher than the field studies. However, several studies have demonstrated that dispersion in the frequency range of 10^{-1} to 10^7 Hz is negligible, thus allowing direct use of the laboratory data in the interpretation of field measurements.

The following tables list velocities in rocks, minerals, polycrystalline aggregates, strata, and other substances available in the published literature. When possible, data have been combined in common tables. To avoid inaccurate extrapolation of individual author's results, some similar tables exist, particularly for velocities at elevated temperatures and pressures.

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