

Hydrated Materials

Applications in Biomedicine
and the Environment

edited by
Yoshitaka Nakanishi



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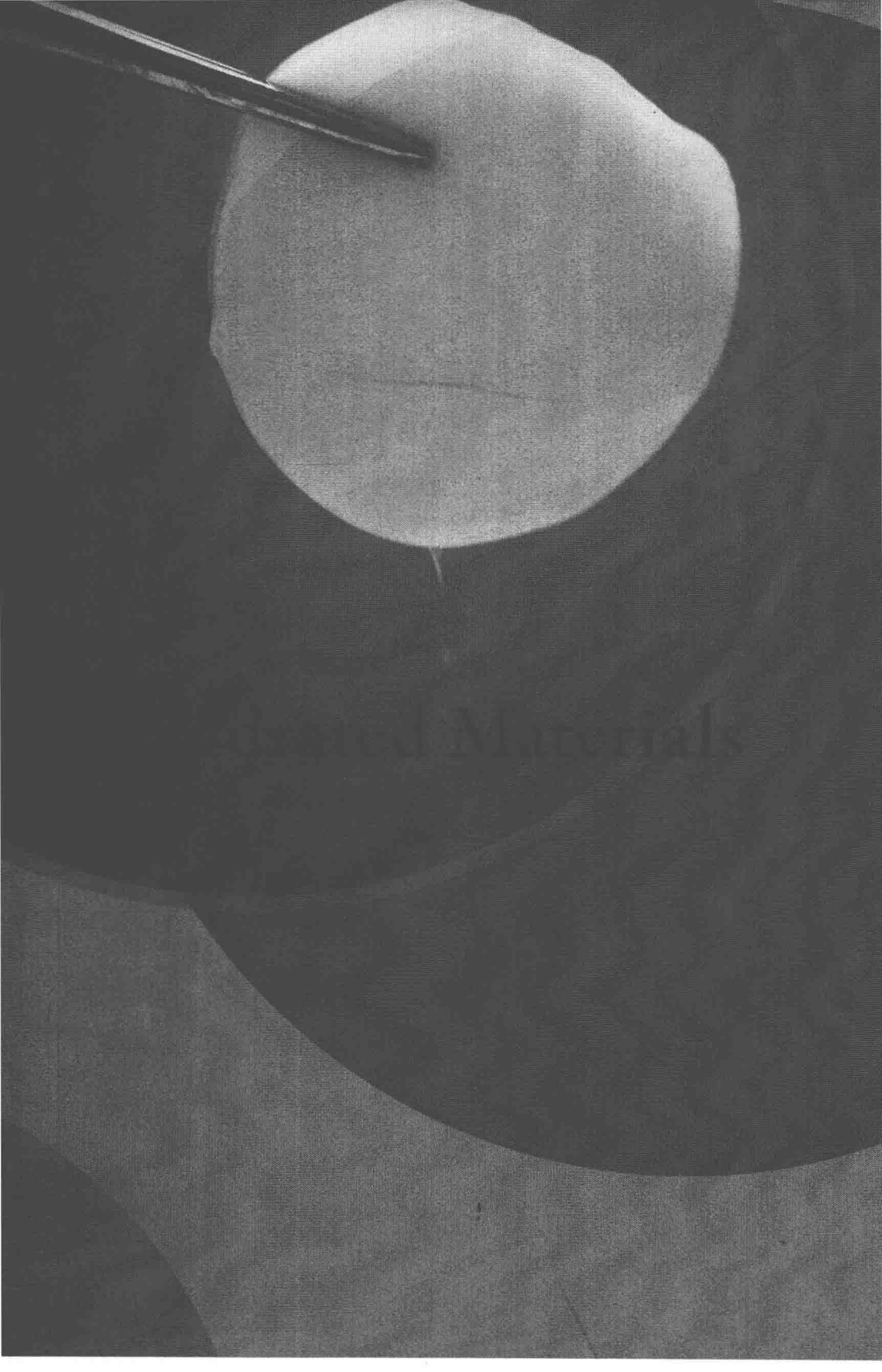
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Coated Materials

Preface

Water covers more than 70% of the earth's surface and is an essential and major component of all living matter. However, artificially hydrated materials, including hydrophilic materials, are far fewer than one might expect. Currently, these materials are in a state of development for applications in fields such as biomedicine, environmental engineering, and industrial engineering. So what do they hold for the future?

This book is a great introduction to hydrated materials for anyone unfamiliar with the topic. Readers can expect this book to be one of the first steps on the path to deepen the understanding of hydrated materials. Within this book they can expect to find academic and practical content, which will give them a feel of both theoretical and real- world problems; fundamental lectures, which will help them to develop a strong knowledge base; examples of latest issues, which will inform them of the direction of current research; hydrated materials defined in a simple manner and explanation for their effective use as a beginner; and a veritable cornucopia of practical examples in a range of fields, which can be employed to fully understand the topic.

I thank all chapter authors for their participation, cooperation, and patience, without which this book would not have been possible.

Yoshitaka Nakanishi

Spring 2015

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Chapter 1

Mechanics of Materials

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1.1 Introduction

When an engineering material or a biological tissue is subjected to forces, it is deformed depending on its mechanical characteristics and the amount and direction of the forces. It is crucial to understand such mechanical response of the material from the standpoint of mechanical design when it is supposed to be used as a part of mechanical device. It is also fundamental to characterise the mechanical behaviour of the tissue from the biomechanical point of view because the remodelling of the tissue is known to be controlled by the mechanical environment surrounding the tissue and its mechanical properties. The macroscopic deformation behaviour of materials is usually characterised by expressing the relationship between the stress and the strain. Fundamental stress-strain relation can be obtained from mechanical tests such as tensile, compression and shear tests. Multi-axial mechanical tests are also sometimes performed to understand more complex mechanical

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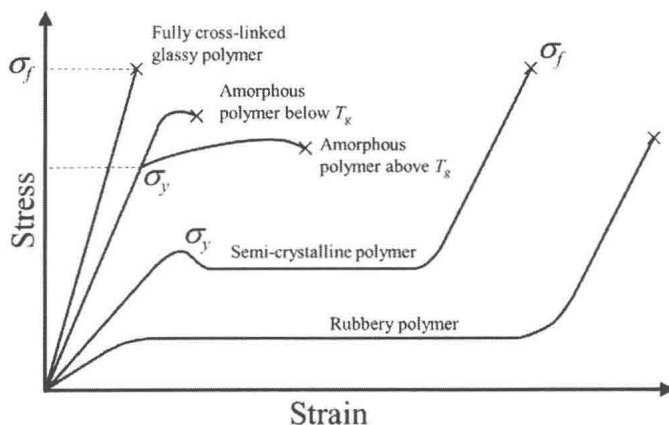


Figure 1.1 Stress–strain behaviour of various kinds of polymer.

response of the materials. The basic mechanical properties such as elastic moduli, Poisson's ratio, yield strength and failure strength are then determined from the testing results obtained. It is however very difficult to characterise the three-dimensional mechanical response of the materials, although in the most of real situations, they are subjected to three-dimensional loadings. As examples, the stress–strain relations of various types of polymers under tensile condition are shown in Fig. 1.1. These macroscopic mechanical characteristics strongly depend on the microstructures and the rheological conditions of macromolecules of the polymers.

The continuum mechanics approaches such as elasticity, viscoelasticity or plasticity have been utilised to theoretically characterise the stress–strain relations of materials and tissues. The elasticity is simply understood to be a mechanics that deals with totally reversible deformation, while the plasticity tries to express irreversible deformation with permanent strain mathematically. The viscoelasticity deals with time-dependent deformations such as creep and stress relaxation. Each of the mechanics theories can be used with equations and material parameters that differ from material to material. Those parameters are usually determined through mechanical tests experimentally.

In this chapter, the basic mathematical formulae appeared in each mechanics theories are described briefly.

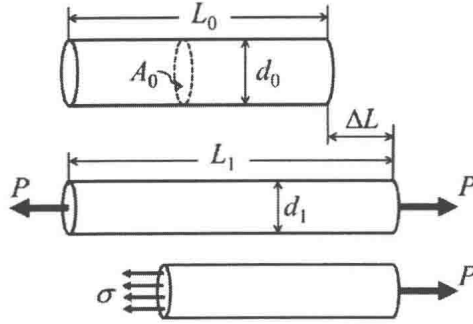


Figure 1.2 Cylindrical rod under tensile loading.

1.2 Strain

When a material is loaded, the change in the material's physical configuration can be described using a non-dimensional quantity called *strain*. Fundamentally, there are two types of strain: *normal strain* and *shear strain*. The normal strain is defined as the extension or compression in the direction of the applied load. As a simple example, we see a round bar subjected to a uniaxial load, as shown in Fig. 1.2. In this case, the strain in the axial direction is defined as:

$$\varepsilon = \frac{L_1 - L_0}{L_0} = \frac{\Delta L}{L_0} \quad (1.1)$$

It is also noted that the bar shrinks uniformly in the lateral direction, and the strain is defined as:

$$\varepsilon' = \frac{d_1 - d_0}{d_0} = \frac{\Delta d}{d_0} \quad (1.2)$$

The ratio of the strain in the lateral direction to the strain in the axial direction is known as *Poisson's ratio* and expressed by:

$$\nu = -\frac{\varepsilon'}{\varepsilon} \quad (1.3)$$

Poisson's ratio is known to be between 0 and 0.5.

A rectangular solid subjected to a shearing force slopes by the angle θ as shown in Fig. 1.3, and the shear strain is defined as:

$$\gamma = \frac{\Delta l}{l} = \tan \theta \approx \theta \quad (1.4)$$

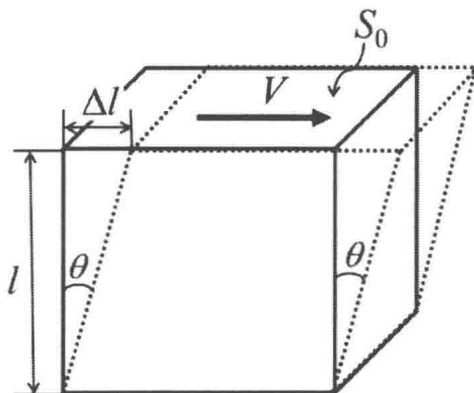


Figure 1.3 Rectangular solid under shear loading.

In general, if it is assumed that all strains are small, the components of normal strain are defined as follows:

$$\varepsilon_x = \frac{\partial u}{\partial x}, \quad \varepsilon_y = \frac{\partial v}{\partial y}, \quad \varepsilon_z = \frac{\partial w}{\partial z} \quad (1.5)$$

where u , v and w are the components of displacement in the x , y and z directions, respectively. Similarly, the components of shear strain are defined by:

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}, \quad \gamma_{yz} = \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}, \quad \gamma_{zx} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \quad (1.6)$$

1.3 Stress

Stress is understood as the transmission of force through deformable materials, and the force acting on the surface of unit area. For example, in a simple uniaxial loading case as shown in Fig. 1.2, *tensile stress* is defined as:

$$\sigma = \frac{P}{A_0} \quad (1.7)$$

Shear stress is also understood as the shearing force acting on the surface of unit area. Therefore, in the rectangular solid subjected to a shearing force V shown in Fig. 1.3, the shear stress is expressed as:

$$\tau = \frac{V}{S_0} \quad (1.8)$$

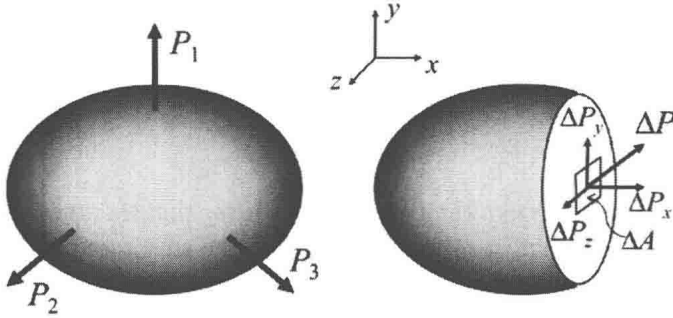


Figure 1.4 An arbitrary solid under three-dimensional loading condition.

We consider a body subjected to a force vector $\mathbf{P}$ having the rectangular components P_1 , P_2 and P_3 as shown in Fig. 1.4. In a certain cross-sectional area perpendicular to the x -axis, the force vector $\Delta \mathbf{P}$ acting on the surface can be decomposed of three components ΔP_x , ΔP_y and ΔP_z . Stress components are then defined as follows:

$$\sigma_x = \lim_{\Delta A \rightarrow 0} \frac{\Delta P_x}{\Delta A}, \quad \tau_{xy} = \lim_{\Delta A \rightarrow 0} \frac{\Delta P_y}{\Delta A}, \quad \tau_{xz} = \lim_{\Delta A \rightarrow 0} \frac{\Delta P_z}{\Delta A} \quad (1.9)$$

In a more general way, an infinitesimally small cube inside of the solid, as shown in Fig. 1.4, is often considered to express stress tensor as illustrated in Fig. 1.5. In this configuration, there are three normal stresses and six shear stresses existing on the surfaces. The

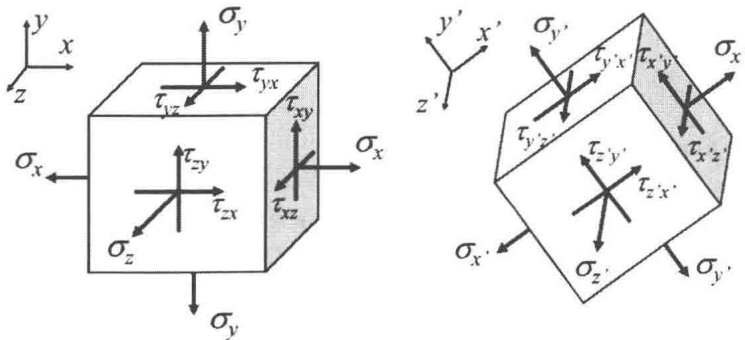


Figure 1.5 Stress components acting on the surfaces of a small cube.

stress tensor is defined by:

$$\sigma = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix} \quad (1.10)$$

It can be proved from the theory of elasticity that this tensor must be symmetric, that is, $\tau_{ij} = \tau_{ji}$. Therefore, the stress tensor actually has three shear components. If the cube is rotated as shown in Fig. 1.5, the stresses in the new position will be related to the original stresses, but they will generally not be the same. The stress components in the original rectangular Cartesian coordinate system x, y, z are expressed by σ_{ij} where $i = 1, 2$ or 3 and $j = 1, 2$ or 3 , corresponding to x, y and z , respectively. Similarly, the stress components in the new coordinate system x', y', z' are denoted by σ'_{km} where $k = 1, 2$ or 3 and $m = 1, 2$ or 3 , corresponding to x', y' and z' , respectively. Then, the stress components are transformed according to the tensor transformation law:

$$\sigma'_{km} = \sigma_{ji} \alpha_{kj} \alpha_{mi} \quad (1.11)$$

where α_{ki} denotes the direction cosine of the x'_k axis ($x'_1 = x', x'_2 = y', x'_3 = z'$) with respect to the x_i axis ($x_1 = x, x_2 = y, x_3 = z$). In these formulae, the summation convention of the index is used.

At every point in a solid, there exists a plane, called a principal plane, where only the normal stress is acting on the plane and there is no shear stress acting on that surface. These normal stresses are called *principal stresses* and usually denoted by σ_1, σ_2 and σ_3 in three-dimensional stress states.

1.4 Constitutive Equations

The mechanical responses of materials are characterised by the relationships between stress and strain from the continuum mechanics point of view. These theoretical descriptions are called *constitutive equations*. A wide variety of materials from soft polymer to hard ceramics exist. Therefore, many constitutive equations describing such variety of materials must be developed.