

GELS HANDBOOK

1

EDITORS-IN-CHIEF

YOSHIHITO OSADA
KANJI KAJIWARA

ASSOCIATE EDITORS

TADAO SHITAMURA
OKIHIKO HIRASA
YOSHITSUGU HIROKAWA
TAKAO FUSHIMI
SHI MATSUNAGA
LIN WANG

TRANSLATED BY

HATSUO ISHIDA



Preface

The development, production, and application of superabsorbent gels is increasing at a remarkable pace. Research involving functional materials in such areas as medical care, medicine, foods, civil engineering, bioengineering, and sports is already widely documented. In the twenty-first century innovative research and development is growing ever more active. Gels are widely expected to be one of the essential solutions to various problems such as limited food resources, environmental preservation, and safeguarding human welfare.

In spite of the clear need for continued gel research and development, there have been no comprehensive references involving gels until now. In 1996, an editorial board led by the main members of the Association of Polymer Gel Research was organized with the primary goal of collecting a broad range of available information and organizing this information in such a way that would be helpful for not only gels scientists, but also for researchers and engineers in other fields. The

xxii *Preface*

content covers all topics ranging from preparation methods, structure, and characteristics to applications, functions, and evaluation methods of gels. It consists of Volume 1, The Fundamentals; Volume 2, Functions; Volume 3, Applications; and Volume 4, Environment: Earth Environment and Gels, which consists of several appendices and an index on gel compounds.

Because we were fortunate enough to receive contributions from the leading researchers on gels in Japan and abroad, we offer this book with great confidence. We would like to thank the editors as well as the authors who willingly contributed despite their very busy schedules.

This handbook was initially proposed by Mr. Shi Matsunaga. It is, of course, due to the neverending effort by him and the editorial staff that this handbook was successfully completed. We would also like to express great appreciation to the enthusiasm and help of Mr. Takashi Yoshida and Ms. Masami Matsukaze of NTS Inc.

Yoshihito Osada
Kanji Kajiwara
November, 1997

Contributors

Editors-in-Chief

Yoshihito Osada, *Professor, Department of Scientific Research, Division of Biology at Hokkaido University Graduate School*

Kanji Kajiwara, *Professor, Department of Technical Art in Material Engineering at Kyoto University of Industrial Art and Textile*

Principal Editorial Members

Tadao Shimomura, *President, Japan Catalytic Polymer Molecule Research Center*

Okihiko Hirasa, *Professor, Department of Education and Domestic Science at Iwate University*

Yoshitsugu Hirokawa, *Technical Councilor, Science and Technology Promotional Office, Hashimoto Phase Separation Structure Project*

xxiv *Contributors*

Takao Fushimi, *Examiner, Patent Office Third Examination Office at Ministry of International Trade and Industry*

Tsutomu Matsunaga, *Director, Chemistry Bio-Tsukuba*

Lin Wang, *Senior Scientist, P&G Product Development Headquarters*

Ito Takeshi, *Assistant Manager, Tokyo Office Sales and Development Division of Mitsubishi Chemical Co.*

Seigo Ouchi, *Head Researcher, Kanishi Test Farm at Agricultural Chemical Research Center of Sumitomo Chemical Co.*

Mitsuo Okano, *Professor, Tokyo Women's Medical College*

Masayoshi Watanabe, *Assistant Professor, Yokohama National University Department of Engineering, Division of Material Engineering*

Contributors

Aizo Yamauchi, *President, International Research Exchange Center of Japan Society of Promotion for Industrial Technology*

Yoshihito Osada, *Professor, Department of Scientific Research in Biology at Hokkaido University Graduate School*

Hidetaka Tobita, *Assistant Professor, Department of Engineering, Material Chemistry Division at Fukui University*

Yutaka Tanaka, *Research Associate, Department of Engineering, Material Chemistry Division at Fukui University*

Shunsuke Hirotsu, *Professor, Department of Life Sciences and Engineering, Division of Organism Structures at Tokyo Institute of Technology*

Mitsuhiro Shibayama, *Professor, Department of Textiles, Polymer Molecule Division at Kyoto University of Industrial Art and Textile*

Hidenori Okuzaki, *Assistant, Department of Chemistry and Biology, Division of Biological Engineering at Yamanashi University*

Kanji Kajiwara, *Professor, Department of Technical Art in Material Engineering at Kyoto University of Industrial Art and Textile*

Yukio Naito, *Head of Research, Biological Research Center for Kao*

(the late) Kobayashi Masamichi, *Honorary Professor, Department of Science, Division of Polymer Molecular Research at Osaka University Graduate School*

- Hidetoshi Oikawa, *Assistant Professor, Emphasis of Research on Higher Order Structural Controls in Department of Reactive Controls at Reactive Chemistry Research Center at Tohoku University*
- Yositsugu Hirokawa, *Technical Councilor, Science and Technology Promotional Office, Hashimoto Phase Separation Structure Project*
- Makoto Suzuki, *Professor, Department of Engineering, Division of Metal Engineering at Tohoku University Graduate School*
- Ken Nakajima, *Special Research, Division of Basic Science in International Frontier Research System Nano-organic Photonics Material Research Team at Physics and Chemistry Research Center*
- Toshio Nishi, *Professor, Department of Engineering Research, Division of Physical Engineering at Tokyo University Graduate School*
- Hidemitsu Kuroko, *Assistant Professor, Department of Life Environment, Division of Life Environment at Nara Women's University*
- Shukei Yasunaga, *Assistant, Department of Technical Art in Material Engineering at Kyoto University of Industrial Art and Textile*
- Mitsue Kobayashi, *Special Researcher, Tokyo Institute of Technology*
- Hajime Saito, *Professor, Department of Science, Division of Life Sciences at Himeji Institute of Technology*
- Hazime Ichijyo, *Manager of Planning Office, Industrial Engineering Research Center in Department of Industrial Engineering, Agency of Industrial Science and Technology at Ministry of International Trade and Industry*
- Masayoshi Watanabe, *Assistant Professor, Yokohama National University Department of Engineering, Division of Material Engineering*
- Kunio Nakamura, *Professor, Department of Agriculture, Division of Food Sciences at College of Dairy Agriculture*
- Hideo Yamazaki, *Shial, Inc. (Temporarily transferred from Tonen Chemical Co.)*
- Koshibe Shigeru, *Shial, Inc. (Temporarily transferred from Tonen Chemical Co.)*
- Hirohisa Yoshida, *Assistant, Department of Engineering, Division of Industrial Chemistry at Tokyo Metropolitan University*

xxvi *Contributors*

Yoshiro Tajitsu, *Professor, Department of Engineering at Yamagata University*

Hotaka Ito, *Instructor, Division of Material Engineering at National Hakodate Technical High School*

Toyoaki Matsuura, *Assistant, Department of Ophthalmology at Nara Prefectural Medical College*

Yoshihiko Masuda, *Lead Researcher, Third Research Division of Japan Catalytic Polymer Molecule Research Center*

Toshio Yanaki, *Researcher, Shiseido Printed Circuit Board Technology Research Center*

Yuzo Kaneko, *Department of Science, Division of Applied Chemistry at Waseda University*

Kiyotaka Sakai, *Professor, Department of Science, Division of Applied Chemistry at Waseda University*

Teruo Okano, *Professor, Medical Engineering Research Institute at Tokyo Women's Medical College*

Shuji Sakohara, *Professor, Department of Engineering, Chemical Engineering Seminar at Hiroshima University*

Jian-Ping Gong, *Assistant Professor, Department of Scientific Research, Division of Biology at Hokkaido University Graduate School*

Akihiko Kikuchi, *Assistant, Medical Engineering Research Institute at Tokyo Women's Medical College*

Shingo Matukawa, *Assistant, Department of Fisheries, Division of Food Production at Tokyo University of Fisheries*

Kenji Hanabusa, *Assistant Professor, Department of Textiles, Division of Functional Polymer Molecules at Shinshu University*

Ohhoh Shirai, *Professor, Department of Textiles, Division of Functional Polymer Molecules at Shinshu University*

Atushi Suzuki, *Assistant Professor, Department of Engineering Research, Division of Artificial Environment Systems at Yokohama National University Graduate School*

Junji Tanaka, *Department of Camera Products Technology, Division Production Engineering, Process Engineering Group at Optical Equipment Headquarters at Minolta, Inc.*

Eiji Nakanishi, *Assistant Professor, Department of Engineering, Division of Material Engineering at Nagoya Institute of Technology*

Ryoichi Kishi, *Department of Polymer Molecules, Functional Soft Material Group in Material Engineering Technology Research Center in Agency of Industrial Science and Technology at Ministry of International Trade and Industry*

Toshio Kurauchi, *Director, Toyota Central Research Center*

Tohru Shiga, *Head Researcher, LB Department of Toyota Central Research Center*

Keiichi Kaneto, *Professor, Department of Information Technology, Division of Electronic Information Technology at Kyushu Institute of Technology*

Kiyohito Koyama, *Professor, Department of Engineering, Material Engineering Division at Yamagata University*

Yoshinobu Asako, *Lead Researcher, Nippon Shokubai Co. Ltd., Tsukuba Research Center*

Tasuku Saito, *General Manager, Research and Development Headquarters, Development Division No. 2 of Bridgestone, Inc.*

Toshihiro Hirai, *Professor, Department of Textiles, Division of Raw Material Development at Shinshu University*

Keizo Ishii, *Manager, Synthetic Technology Research Center at Japan Paints, Inc.*

Yoshito Ikada, *Professor, Organism Medical Engineering Research Center at Kyoto University*

Lin Wang, *Senior Scientist, P&G Product Development Headquarters*

Rezai E., *P&G Product Development Headquarters*

Fumiaki Matsuzaki, *Group Leader, Department of Polymer Molecule Science Research, Shiseido Printed Circuit Board Technology Research Center*

xxviii *Contributors*

Jian-Zhang (Kenchu) Yang, *Researcher, Beauty Care Product Division of P&G Product Development Headquarters*

Chun Lou Xiao, *Section Leader, Beauty Care Product Division of P&G Product Development Headquarters*

Yasunari Nakama, *Councilor, Shiseido Printed Circuit Board Technology Research Center*

Keisuke Sakuda, *Assistant Director, Fragrance Development Research Center at Ogawa Perfumes, Co.*

Akio Usui, *Thermofilm, Co.*

Mitsuharu Tominaga, *Executive Director, Fuji Light Technology, Inc.*

Takashi Naoi, *Head Researcher, Ashikaga Research Center of Fuji Film, Inc.*

Makoto Ichikawa, *Lion, Corp. Better Living Research Center*

Takamitsu Tamura, *Lion, Corp. Material Engineering Center*

Takao Fushimi, *Examiner, Patent Office Third Examination Office at Ministry of International Trade and Industry*

Kohichi Nakazato, *Integrated Culture Research Institute, Division of Life Environment (Chemistry) at Tokyo University Graduate School*

Masayuki Yamato, *Researcher, Doctor at Japan Society for the Promotion of Science, and Japan Medical Engineering Research Institute of Tokyo Women's Medical College*

Toshihiko Hayasi, *Professor, Integrated Culture Research Institute, Division of Life Environment (Chemistry) at Tokyo University Graduate School*

Naoki Negishi, *Assistant Professor, Department of Cosmetic Surgery at Tokyo Women's Medical College*

Mikihiro Nozaki, *Professor, Department of Cosmetic Surgery at Tokyo Women's Medical College*

Yoshiharu Machida, *Professor, Department of Medical Pharmacology Research at Hoshi College of Pharmacy*

Naoki Nagai, *Professor, Department of Pharmacology at Hoshi College of Pharmacy*

Kenji Sugibayashi, *Assistant Professor, Department of Pharmacology at Josai University*

Yohken Morimoto, *Department Chair Professor, Department of Pharmacology at Josai University*

Toshio Inaki, *Manager, Division of Formulation Research in Fuji Research Center of Kyowa, Inc.*

Seiichi Aiba, *Manager, Department of Organic Functional Materials, Division of Functional Polymer Molecule Research, Osaka Industrial Engineering Research Center of Agency of Industrial Science and Technology at Ministry of International Trade and Industry*

Masakatsu Yonese, *Professor, Department of Pharmacology, Division of Pharmacology Materials at Nagoya City University*

Etsuo Kokufuta, *Professor, Department of Applied Biology at Tsukuba University*

Hiroo Iwata, *Assistant Professor, Organism Medical Engineering Research Center at Kyoto University*

Seigo Ouchi, *Head Researcher, Agricultural Chemical Research Center at Sumitomo Chemical Engineering, Co.*

Ryoichi Oshiumi, *Former Engineering Manager, Nippon Shokubai Co. Ltd. Water-absorbent Resin Engineering Research Association*

Tatsuro Toyoda, *Nishikawa Rubber Engineering, Inc. Industrial Material Division*

Nobuyuki Harada, *Researcher, Third Research Division of Japan Catalytic Polymer Molecule Research Center*

Osamu Tanaka, *Engineering Manager, Ask Techno Construction, Inc.*

Mitsuharu Ohsawa, *Group Leader, Fire Resistance Systems Group of Kenzai Techno Research Center*

Takeshi Kawachi, *Office Manager, Chemical Research Division of Ohbayashi Engineering Research Center, Inc.*

Hiroaki Takayanagi, *Head Researcher, Functional Chemistry Research Center in Yokohama Research Center of Mitsubishi Chemical, Inc.*

Yuichi Mori, *Guest Professor, Department of Science and Engineering Research Center at Waseda University*

xxx *Contributors*

Tomoki Gomi, *Assistant Lead Researcher, Third Research Division of Japan Catalytic Polymer Molecule Research Center*

Katsumi Kuboshima, *President, Kuboshima Engineering Company*

Hiroyuki Kakiuchi, *Mitsubishi Chemical, Inc., Tsukuba Research Center*

Baba Yoshinobu, *Professor, Department of Pharmacology, Division of Pharmacological Sciences and Chemistry at Tokushima University*

Toshiyuki Osawa, *Acting Manager, Engineer, Thermal Division NA-PT at Shotsu Office of Ricoh, Inc.*

Kazuo Okuyama, *Assistant Councilor, Membrane Research Laboratory, Asahi Chemical Industry Co., Ltd.*

Takahiro Saito, *Yokohama National University Graduate School, Department of Engineering, Division of Engineering Research*

Yoshiro Sakai, *Professor, Department of Engineering, Division of Applied Chemistry at Ehime University*

Seisuke Tomita, *Managing Director, Development and Production Headquarters at Bridgestone Sports, Inc.*

Hiroshi Kasahara, *Taikisha, Inc. Environment System Office*

Shigeru Sato, *Head Researcher, Engineering Development Center at Kurita Engineering, Inc.*

Okihiko Hirasa, *Professor, Iwate University*

Seiro Nishio, *Former Member of Disposable Diaper Technology and Environment Group of Japan Sanitary Material Engineering Association*

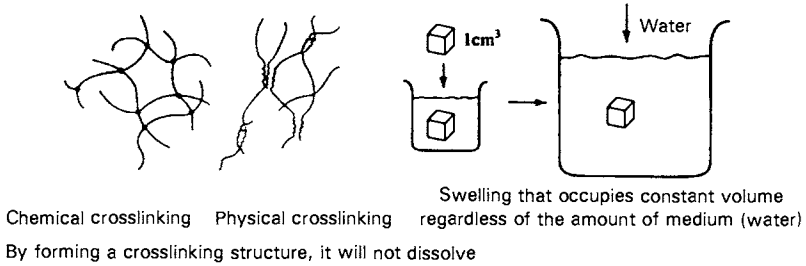
Section 1

Gels: Introduction

AIZO YAMAUCHI

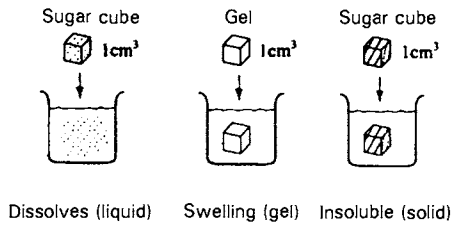
1.1 WHAT ARE GELS?

According to the newly edited version of the *Polymer Dictionary* [3], gels are defined as “polymers and their swollen matters with three-dimensional network structures that are insoluble in any solvents.” Also see References [1] and [2] for what constitutes a gel. The dictionary also states that the relationship between the crosslinked structure of gels and characteristics of swelling matter is one in which “linear and branched polymers absorb, swell, and eventually disperse as individual molecules into good solvents. On the other hand, the degree of swelling of crosslinked polymers is limited due to the three-dimensional network structure, although they can swell by the interaction with the solvent.” It also notes that gels exist under special conditions not found in solids, liquids, and gases: “swollen gels that have absorbed a large amount of solvent are in the states between solids and liquids and their properties change from viscous liquids to hard solids according to the chemical composition and other factors.” Gelation occurs via crosslinking. However, crosslinking does not necessarily require covalent bond formation. It can also be achieved by secondary forces as seen in hydrogen bonding. Thus, gels are crosslinked three-



(a) Crosslinked structure

(b) Swelling



(c) Intermediate between liquid and solid

Fig. 1 Schematic diagrams of solution, gel, and solid.

dimensional (3D) networks, absorb solvents, and swell to a limited degree without dissolution. In addition, they exist in states that are somewhere between a solid and a liquid. See Fig. 1 for elucidation.

1.2 CLASSIFICATION

A gel consists of both a 3D network structure and a medium. Although it is possible for the medium to be a gas, it is generally a liquid. It will be considered here that gels are 3D network polymers swollen by liquids (solvents). Gels are classified based on the type of crosslinking that creates their 3D networks, as well as whether they are natural or artificial, the shape and size of the gel configuration, and the types of solvents. Table 1 presents many of the classifications of gels to which this work will refer.

1.2.1 Method of Crosslink Formation

Gels can be formed via covalent bonding, the coulombic force, hydrogen bonding, and coordination bonding, and although physical interaction

6 Chapter 1: Section 1 Gels: Introduction

Table 1 Classification of gels.

Crosslinking system (semi-crosslinking)	Covalent bonding	Crosslinking agent · chemical cross linking
	Coulombic force	Light · radiaton
	Hydrogen bonding	Polyelectrolytes
	Coordination bonding	Natural gels, frozen gels
	Entanglement	Small molecules · ions High degrees of polymerization, branched, weak in strength
Structural polymers	Natural gels	Food, protein, polysaccharides, tissues living in the natural world
	Hybrid gels	Medical materials, artificial skin, artificial corneas, artificial pancreas model
	Synthetic gels	Organic polymer, contact lenses, high water absorbent resins, silica gels
Configuration size	Micro-gel	Intramolecular crosslinking: does not enlarge
	Macro-gel	Intermolecular crosslinking: normal gel
Solvent	Air	Aerogel, Xerogel
	Water	Hydrogel
	Oil	Lyopic (organo) gel

(such as entanglement) is not a form of chemical crosslinking, gels can be formed this way. Most synthetic matter is of the covalent bonding type, generally polymerized by adding crosslinking agents when polymers are synthesized. The crosslinked structure is strong. Those gels using coulombic force are poly-ion complexes between polyelectrolytes with opposite charges or polyelectrolytes with multivalent ions, such as calcium.

The gels liquefy and a sol-gel transition occurs when the coulombic force is overcome by changing either pH or ionic strength. The hydrogen bonding system, created when crosslinked structures are formed by hydrogen bonding between the polymers, is seen mostly in natural matter. In these cases, gels will change to sols when hydrogen bonding is broken by the environment, for example, by heating. Coordination bonding is created when crosslinked structures are formed between polar groups of a polymer and the material that is coordinated. Situations that do not involve crosslinking were mentioned previously. Polymer chains become entangled and a gel is created when the molecular weight of the polymer is large or there is branching. In this case, the crosslink point

is not specified and the gel configuration is unstable. As bonding strength is weak, in time it will disperse in the solvent and dissolve.

1.2.2 Natural Gels and Synthetic Gels

Typical gelled foods from ancient times are gels that were created using natural materials. Because they are made of natural polymers, there are many forms of polysaccharides and proteins such as in kon-nyaku (a gelatinous cake made of the root of devil's tongue) and tofu. On the other hand, the superabsorbent disposable diapers, perfumes, and contact lenses we use daily are gels made of water soluble, synthetic polymers such as poly(vinyl alcohol) and poly(hydroxyethyl methacrylate). It is possible for them to be made of either a single component or multicomponents. There has been much attention given to the hybrid gels used in medicine and biotechnology due to their improved compatibility with bioorganisms, which allow organic components to assimilate synthetic materials, as well as for special bioorganic functions to be added to gels. As organisms, excluding hard structures like bones and teeth, are composed mostly of water and yet can maintain their shapes in water, it is not an exaggeration to state that human bodies are made mostly of gels. This can be understood if one examines the cornea, lens, or vitreous humor of the eye, or neuronal tissue, all of which are gels. Modern medicine anticipates using hybrid gels capable of fusing, with an organism. These include, but are not limited to, artificial skin [4] and corneas [5].

1.2.3 The Crosslink Structure and Size

Although 3D crosslinked structures are usually shown using a lattice model, in reality, polymers can be rather spread out or coiled up into a ball, depending on the relationship between them and their solvent (one such relationship is the solubility parameter). There are heterogeneous gels in which crosslinked units are locally concentrated and homogeneous gels with evenly distributed crosslinked units. The conceptual diagram for crosslinked structures is shown in Fig. 2. When the size of a gel network is to be given, the average molecular weight between the crosslinked units can be used. The spatial size of a substance can also be determined by measuring the permeation of water and solutes in the medium. In the former, there are calculation methods for degree of swelling that use the Flory formula or the dynamic modulus. The latter is more practical as it is

8 Chapter 1: Section 1 Gels: Introduction

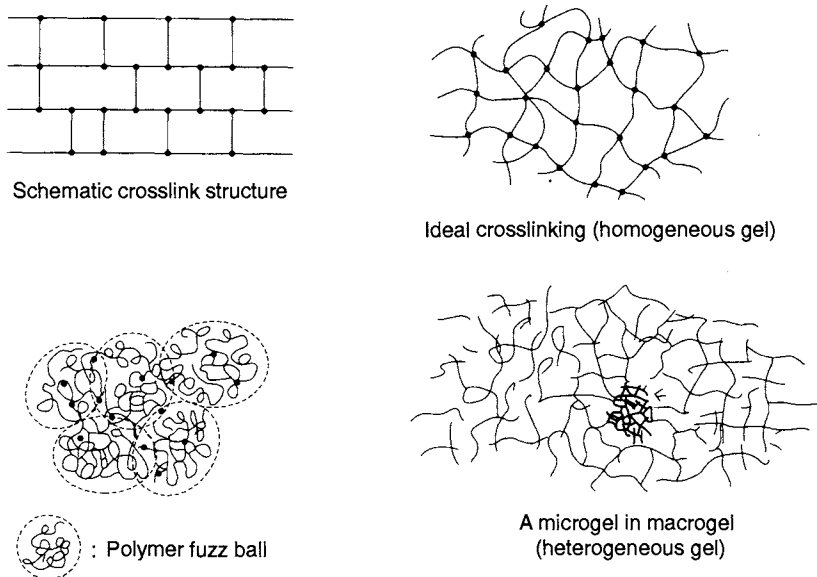


Fig. 2 Schematic diagram of crosslink points.

often important for actual applications of gels, such as the permeability of membranes and their control release properties. There are equations to calculate these quantities by measuring diffusion through membrane of penetrants of known size, such as cells, enzymes, certain proteins and dyes, or the permeability of water under pressure.

Table 2 provides comparisons of network size using the gel membrane of a relatively homogeneous network structure. This network structure was crosslinked by the free radical reaction initiated by γ -ray

Table 2 Size of networks (nm) [6].

Swelling ratio ^a	Pore radius from water permeability	Average distance between crosslink points	
		From swelling ratio	From modulus
8.77	1.7	18	11
11.9	1.9	27	16
15.3	2.5	36	21
17.8	2.7	43	25

^aWeight of swelling gel/weight of dried gel

irradiation on a poly(vinyl alcohol) aqueous solution. The mean distance between crosslinked units almost matches, but the size calculated from the water permeability is one order of magnitude smaller. The point of this calculation was to obtain the mean radius of the pores when water passes through the hydrated polymer fuzzi balls.

1.2.4 Microgels and Macrogels

With respect to the size of gels, there are microgels and macrogels. In a dilute solution, the distance to other molecules is larger, making intermolecular crosslinking more difficult. This creates intramolecular crosslinking of the same polymer chain and crosslinking among several molecules. The spreading of molecules due to crosslinking leads to local concentration fluctuations. Subsequently, the probability of contact with polymer chains becomes less, thereby creating microgels. The compatibility of microgels with solvents diminishes as crosslinking progresses. These microgels sometimes precipitate as ultrasmall particles. However, regardless of whether they precipitate or not, microgels consist of one to several polymer molecules in which each of the polymers holds crosslinked units. This makes them fundamentally different from polymer solutions (sols) that are homogeneously dissolved in the solvent as molecules, without having crosslinked units. These microgels are dispersed in a medium and have been used as the basic material in paints. Painting a surface is easier because the particles adhere and create a strong film after drying. Gels are typically bulks made of, in extreme cases, single, giant molecules; such gels are called macrogels. These giant molecules consist of polymer chains connected by crosslinking.

The distribution of crosslinked units inside macrogels is not uniform. For example, when crosslinking is induced by light, the higher energy flux on the surface than on the inside tends to create higher crosslink density on the outside. This makes it possible to create a skin-core morphology in the gel. When a gel is formed by simultaneous polymerization and crosslinking of a monomer and crosslinking agent, it is necessary to consider carefully the reaction conditions, including concentration and temperature. Especially important is the reactivity ratio of the monomer and crosslinking agent. When their reactivity is very different, a preferential crosslinking reaction takes place at the beginning and end of polymerization and localized crosslinks appear in the macrogel. This is schematically shown in Fig. 3. This is called microgelation within a

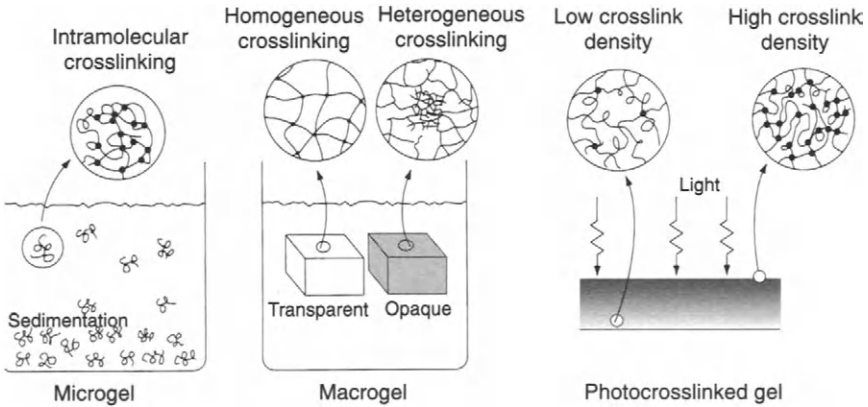


Fig. 3 Heterogeneous crosslinking.

macrogel, and is one reason why gels become heterogeneous. In this case, when the microgels become heterogeneous on the order of the wavelength of light, the light scatters. This creates an opaque, fragile gel even if the homogeneous gel is clear. As the network size is uneven, it is then important to be cautious when the goal is to use the separation by network effect (i.e., preparation of an electrophoresis gel).

1.2.5 Medium

When water is the medium for a gel, it is called a hydrogel. However, most gels, whether natural or synthetic, are composed of water. Therefore, when speaking of gels, we generally refer to water-medium gels. In addition, there are lyopic gels (also called organogels), which are created from an oil-medium such as silicone oil. These have gained attention in recent years as a shock absorption material in tennis shoes. In a broader sense, there are aerogels or xerogels, which use air as the medium; these include silica gels, dried agar and Kouya tofu (freeze-dried tofu). However, these are not normally considered to be gels.

1.3 THREE-DIMENSIONAL CROSSLINK STRUCTURE AND NETWORKS

It is necessary for gels to have intermolecular crosslink structures of polymers, that is, polymer networks. These networks can range in size

from a large scale of 10^3 – 10^6 m (Internet-sized) to human networks used for direct interaction at 1–10 m, all the way down to a network of 10^{-3} –1 m for daily necessities such as nylon stockings, textiles, bamboo baskets, and wire netting. A polymer network is very fine at 10^{-9} – 10^{-6} m. The universal function of any network is to incorporate correct matter. On a large scale the Internet has enveloped the earth and, on a small scale, bird cages protect birds by keeping them in. Similarly, gel networks create very small spaces and special environments. In these spaces, various functions are observed in any organism in which gels originate; they include filtering, diffusion, and atomic or molecular order interactions between the polymer chains and the enclosed solute or solvent. Inside the 3D crosslinked structure, there is a microspace where closely packed polymer chains, solvent, and solute coexist.

Although it is not possible to prepare a polymer solution with a high concentration (50–70%) using high molecular weight polymers, it is possible in a gel system to study the interaction of polymers in a high density system with solvent or solute by taking advantage of gels that exist in a state between liquid and solid. Especially in organisms, purposeful and precise structures are formed and high performance can be obtained

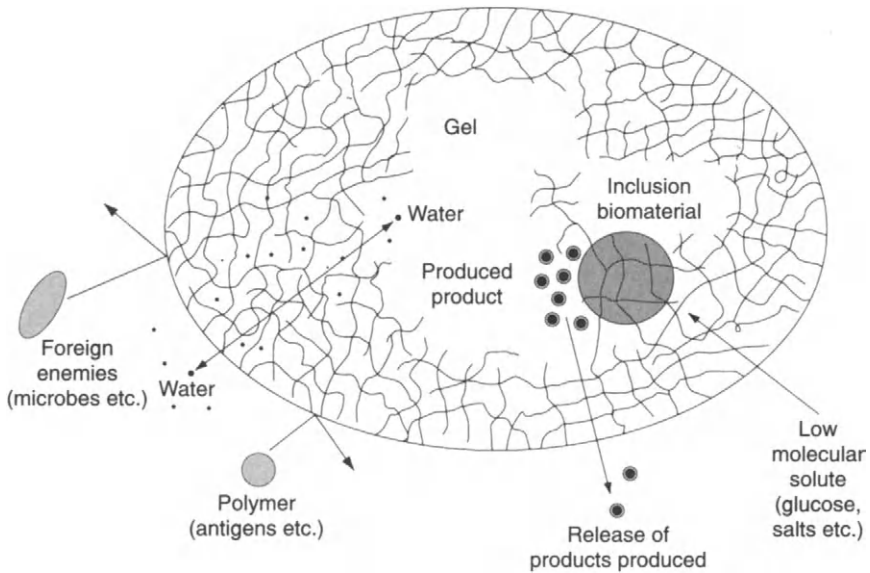


Fig. 4 Role of network structures.

because biopolymer synthesis, crosslinking, and gelation take place simultaneously in organisms. In a hybrid gel with bioorganisms, for example, it is possible to study an artificial pancreas where rejection is avoided by the insertion of a cell colony (i.e., the islets of Langerhans) while insulin is released into the body using gel networks. Accordingly, the gel's precise network structure is one that presents a wall to the outside world and a channel that allows the necessary materials to flow in. This network also serves as a control in an internal microscopic environment (see Fig. 4).

1.4 OTHER USES

The most famous gel is the soft contact lens developed in Czechoslovakia in 1960 using poly(hydroxyethyl methacrylate). In the late 1970s, super-absorbent polymers were developed in the United States and their use in feminine products was worldwide. In 1980, Professor Toyochi Tanaka discovered phase transition in gels. Today many researchers study those transitions from the basics to applications. Gel applications or functional uses due to phase transitions are found in the chapters that follow and will not be discussed here.

REFERENCES

- 1 Yamauchi, A., and Hirokawa, Y. (1990). *Functional Gels, New Polymeric Materials*. Society for High Polymers, ed., Kyoritsu Publ. p. 3.
- 2 Ogino, I., Osada, Y., Fushimi, T., and Yamauchi, A. (1991). *Gels*, Sangyo Tosho, p. 3.
- 3 *New Edition of Polymer Dictionary* (1988). Society for High Polymers, ed., Asakura Shoten, p. 129.
- 4 Kuroyanagi, Y. (1995). Frontier of artificial skin, *Kobunshi*, **44**: 570.
- 5 Nakao, H., Matsuda, T., Saishin, M., *et al.* (1993; 1994). Development of hybrid artificial cornea 1,2,3, *Ganki*, **44**: 247; **44**: 1107; **45**: 614.
- 6 Yamauchi, A. (1977). Composition and structure of gels, *Protein, Nucleic Acid and Enzymes*, **22**: (13), 46.