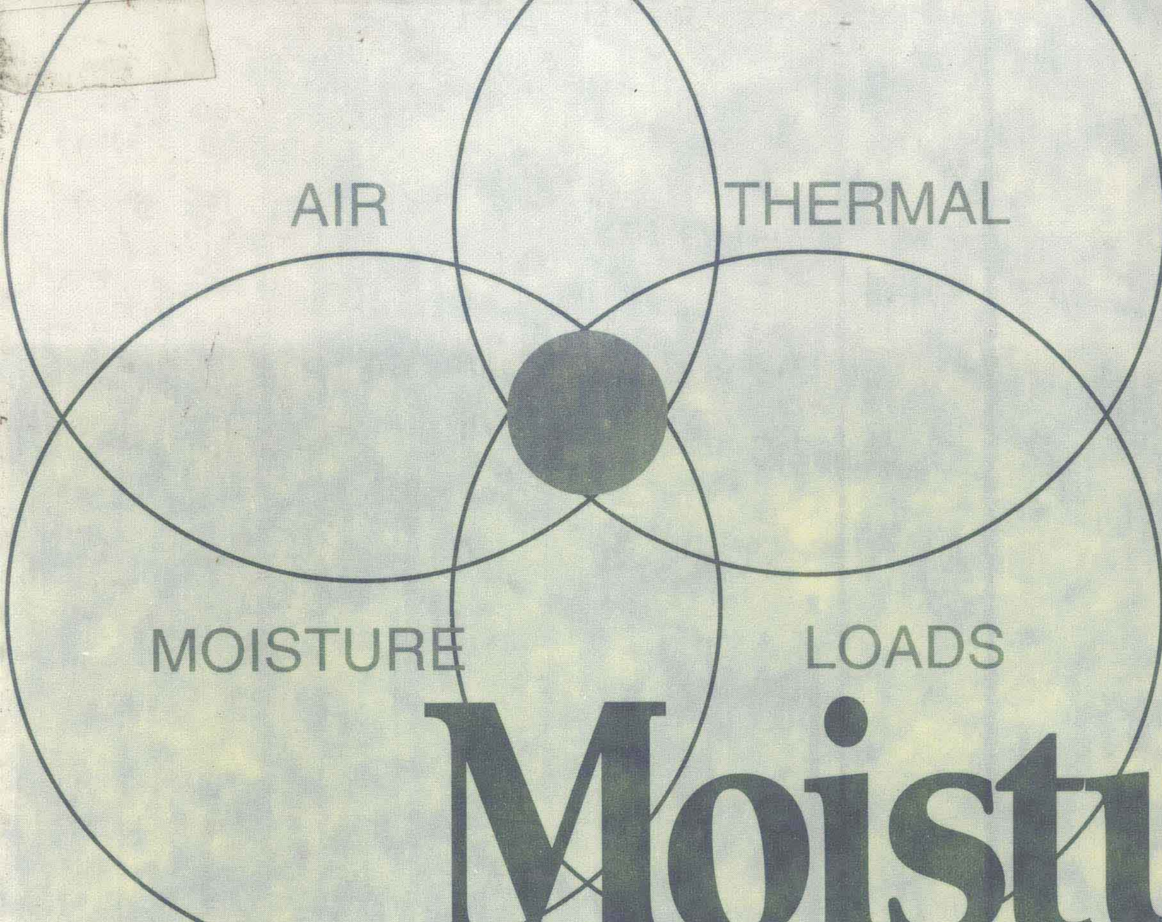

Moisture Control in Buildings

HEINZ R. TRECHSEL, EDITOR

ASTM

Moisture Control in Buildings

Heinz R. Trechsel, Editor

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NOTE: This manual does not purport to address (all of) the safety problems associated with its use. It is the responsibility of the user of this manual to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

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February 1994

Dedication

Wayne P. Ellis
1915–1993

Former Chairman of the Board of ASTM, Standards Consultant, First Chairman of the Board of the Building Environment and Thermal Envelope Council

As all those who were close to Wayne Ellis know, his foremost interest in his later years was terminology, but the issue of moisture control in buildings was also one of his concerns.

It was Wayne who, in the mid-1970s, encouraged the formation of a joint Committee C16/E06 ad hock task force on moisture control, who helped expand that task force to include members of ASHRAE and other groups, and who agreed to the establishment of that task force on a more permanent basis as the Research Coordinating Committee on Moisture within the Building Environment and Thermal Envelope Council under the auspices of the National Institute of Building Sciences.

It was also Wayne who encouraged the Editor to undertake the development of this manual. He provided his valuable advice all along the tortuous route from conception to final approval of the manuscript. His own chapter, "Applicable Guidelines, Standards, and Codes," will unfortunately remain the last of his many contributions to ASTM publications.

With these thoughts in mind, the authors and I dedicate this manual to our friend, contributor, and mentor, Wayne P. Ellis.

Heinz Trechsel
Editor

Acknowledgments

I WISH TO THANK THE AUTHORS for their contributions. Unlike the preparation of technical papers for symposia, conferences, and workshops, the preparation of a chapter within the framework of a manual is more difficult and more time consuming. I apologize to the authors for imposing strict and sometimes unreasonable deadlines, but they were necessary to keep the material timely.

A major role in the preparation and publication of any ASTM publication falls to the reviewers. Their names are listed below in alphabetical order. Their contribution is vital to a good and technically solid manual. Many thanks to all of them.

One reviewer undertook the enormous task of reading each and every chapter to help achieve a measure of overall completeness and uniformity in quality. It is my pleasure to thank Dr. Ervin Bales of the New Jersey Institute of Technology for this great help. During the development of the book proposal, Paul Reece Achenbach, former director of the Building Environment Division at the National Institute for Standards and Technology, and Wayne P. Ellis, Past President of ASTM, acted as sounding boards for various ideas relating to the manual. Their valuable counsel and consistent encouragement is gratefully acknowledged.

This manual required a myriad of tasks, from preparing author agreements to tracking down addresses of potential reviewers, preparing final drawings, book design, and editing. All these tasks fell to the staff of the ASTM Publication and Marketing Division. As always, they performed splendidly, and without their help not even the book proposal would have seen the light of day. My very best thanks to Kathleen A. Dernoga and Monica Siperko of Acquisition and Review, to David Jones, the copyeditor, of Books and Journals, and to Jonathan Bruno of Design Works, Bryn Mawr, PA, who helped illustrate the manual.

Last, but not least, my thanks go to my wife Gisela for her understanding, support, and encouragement during the four years from initial outline to final publication.

Heinz Trechsel
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Preface

WELL-DEFINED AND soundly constructed buildings have many virtues, among them the ability to serve their intended purpose, to provide a pleasant and esthetic environment, and to become an essential and beautiful backdrop for human life. Furthermore, buildings must be structurally sound and resist loads, such as their own weight, the weight of occupants and contents, wind, and seismic loads. They must keep out rain and other elements; they must provide a healthy indoor environment with regard to heating and cooling and in terms of indoor air pollutants; and they must maintain their functions over an extended service life.

All these functions are directly affected by moisture. Uncontrolled moisture will reduce the structural soundness of buildings through dry rot in wood and corrosion in steel. Moisture affects the health of occupants directly and through the potential for breeding harmful organisms. Moisture can reduce the service life through premature degradation of components. In short, uncontrolled moisture will negate the most vital and important qualities of buildings. On the other hand, moisture reduces the drying out and shrinking of wood products and furniture, and, up to a point, will alleviate upper respiratory discomfort. Thus, moisture is both a necessary constituency of our environment and a potential liability. The issue, then, is not to eliminate moisture from our buildings, but to control it both within the building interior as well as within building components and materials.

According to ASTM Practices for Increasing Durability of Building Constructions Against Water-Induced Damage (E 241), "except for structural errors, about 90 percent of all building construction problems are associated with water in some way." It is therefore understandable that much information on moisture in buildings is available, and that many books and technical papers have been written over the last 50 years on the subject of moisture and moisture control in buildings. A complete library of books, reports, technical papers and monograms, standards, and data relating to moisture control in buildings would include several thousand titles, and the serious researcher concerned with this field may quite regularly peruse several hundred.

Several good reference documents include sections on moisture control in buildings. A short bibliography of useful reference publications is provided at the end of this manual. In addition, many technical publications and conference proceedings by various organizations such as ASTM, ASHRAE, and BETEC are available and contain valuable research papers on moisture control in buildings. Also, much information on moisture in buildings is scattered throughout the literature as technical reports prepared by research organizations such as the National Institute for Standards and Technology, the Forest Products Laboratory, Oak Ridge National Laboratory, and Princeton University. However, much of that literature is difficult to obtain and access. Many such texts are referenced in the various chapters of this manual. All these publications are valuable and are highly recommended to those interested in the subject of moisture control in buildings in general or in any particular aspect of it.

However, there has been to date no publication which provides a comprehensive overview of the various issues and data related to moisture control in buildings. It is the intent of this manual to provide such an overview, to bring together in one volume the most important data and applicable state of the art relating to moisture problems in buildings, their diagnosis, prevention, and rehabilitation, and to synthesize the existing information and technology as a basis for indicating good design practice. It is the hope of the authors and the editor that this volume will serve as a desk-top reference manual for use by those who design, construct, sell, maintain, and own buildings and homes. The chapters on standards and codes, contract documents, and legal aspects of moisture control should aid in understanding the various mechanisms available for effective implementation of moisture control strategies.

Given the critical nature of moisture control in buildings, it is not surprising that early literature treated moisture as a separate, serious, distinct, and most important potential problem in building construction. However, since about 1974, the need for energy conservation has moved into a commanding position as the major concern in building performance, crowding out moisture as a primary concern. In addition, some energy conservation measures, such as the reduction of infiltration and ventilation, were applied unthinkingly and with little regard to the overall performance of buildings, sometimes causing moisture problems as side effects. As a result, concerns for moisture were relegated to a position of unfortunate, and possibly even apparently necessary, side effects of energy conservation measures. Because of this, those who promoted energy conservation were expected to solve moisture problems as well.

Of course, well-designed and installed energy conservation measures, be it in new or existing buildings, do not "cause" moisture problems, although inept application of some energy conservation measures can increase the propensity for moisture problems in already marginal structures. And, similarly, most moisture problems in buildings have causes other than energy efficiency. What both energy inefficiency and moisture problems have in common are poor design and a lack of understanding of how buildings and their equipment perform under the varied conditions of climate and occupancy. Great strides have been made in the development of technology to increase energy efficiency, to the point that energy-efficient building design has evolved into an interdisciplinary science. Moisture control in buildings has also made great strides over the last few years. ASTM has held several symposia and conferences and has published proceedings. Other organizations have done likewise, and the number of moisture-related technical contributions to national building technology conferences has increased significantly. For example, the second ASHRAE Conferences on Thermal Performance of Exterior Envelopes of Buildings in 1982 included seven papers on moisture control; the fifth similar conference in 1993 contained 17 papers on moisture. However, even today, moisture resistance is not, as a matter of code requirements, routinely designed into buildings as is structural integrity or temperature control because moisture, in the past, was not considered related to health and safety despite the long-recognized fact that moisture can lead to deterioration and eventual failure of the structure and the more recent recognition of detrimental health effects.

Accordingly, moisture control is not currently recognized as a separate and essential part of building technology. Even in such prestigious publications as the *ASHRAE Handbook on Fundamentals* and the *Architectural Graphics Standard*, moisture control is not treated as a separate subject; rather, parts are scattered over several chapters.

One objective of this manual is to help establish moisture control in buildings as a separate and major branch of building technology and building sciences. As such, moisture control must draw from many established sciences and technologies: the physics of heat and moisture transfer, material sciences, biology and health sciences, computer simulations, and others. For most of these, this manual will provide a basis of knowledge and data needed to prevent, investigate, and solve the most common moisture problems. Beyond the information and data provided in this manual, the referenced sources should provide the missing data and information for those who wish to study the issues more deeply.

From the beginning of the development of the book proposal and periodically thereafter, the question was raised as to who the intended audience was. We believe the manual will be useful to all those involved in designing and maintaining moisture-resistant buildings and in solving and repairing moisture problems in existing buildings: architects, owners, maintenance personnel, investors, researchers, and those who have to settle disputes resulting from moisture damage. For those who are experts within a particular area or chapter of the manual, the material covering such expertise may not be of great value as they, being experts, will have readily available specialized handbooks and other technical literature. Thus, the physicist will learn little from Chapter 1 on the fundamentals of moisture transport, condensation, and evaporation, and the mechanical engineer may find Chapter 2 on modeling heat, air, and moisture transport through building materials on components too general and basic for his needs. However, all experts and lay persons will benefit from the chapters outside their area of expertise.

This publication did not rely on a call for papers to solicit contributors. Rather, a book outline was prepared by the editor with input from many experts and was reviewed and approved by the ASTM Committee on Publications. Chapter authors were then selected based on expertise in their field. It was my task as editor to assure that the individual chapters conformed in a general way to the original outline and to reduce the number of conflicts and repetitions.

Were moisture control in buildings a mature science, this manual would contain no or only minor and infrequent conflicts or inconsistencies between the findings of one researcher or practitioner and others. But moisture control is not a mature science and therefore some of the foremost experts, researchers, and practitioners disagree on major issues. Where such disagreements have occurred, they were retained. So that each chapter might stand on its own, we also did not eliminate repetitions. Finally, although each chapter has undergone a rigorous peer review by three qualified reviewers, the manual is not a consensus document in the sense that ASTM uses the term, and the recommendations given in individual chapters are not necessarily those of ASTM or of the sponsoring committees, Committee E06 on Performance of Buildings and C16 on Thermal Insulation.

It is the hope of the authors and the editor that this manual will identify some of the knowledge gaps, will lead to more research for developing a more complete understanding of all aspects of moisture control in buildings, and will help to establish moisture control as a recognized, interdisciplinary engineering discipline much like that of energy conservation.

Heinz R. Trechsel
Editor

Introduction

THIS MANUAL strives to provide the major needed information and data to design and maintain moisture-resistant buildings and to investigate and correct moisture problems in existing buildings. It contains individual chapters devoted to the primary disciplines and mechanisms that promote and resist moisture-induced damage. To be responsive to the perceived need, it was essential to include in the manual many disciplines, types of investigators, theoreticians, and practitioners. Because these individuals do not currently agree in all aspects with one another, there are some conflicts and inconsistencies between the individual chapters.

As mentioned in the Preface, the main concern of building design is the development of structures for human habitation that are safe, provide a healthy and pleasant environment, and maintain these functions over a long service life. Since moisture affects all three, concerns for effective moisture control must be an integral part of the design process. This manual attempts to bring together in one volume the current state of the art relating to moisture control in buildings (good design practices), diagnosis and prevention of moisture-originated damage, and guidelines for rehabilitation of the structures. The manual addresses residential, commercial, and institutional buildings in all North American climatic zones. In all jurisdictions, design professionals are required to follow accepted standards of practice, but for many issues on moisture, accepted standards and practices are few or missing altogether and others are outdated by the development of new materials, new combinations of old materials into new systems, and new insights into the behavior of materials and structures.

The publication of this manual responds not only to the increasing awareness of the long-known potential structural and maintenance problems resulting from inadequate moisture control, but also to the more recently recognized and potentially even more serious health hazards of rot, mold, and other organisms which flourish in buildings with excessive moisture, or in localized areas with a conducive combination of moisture and temperature. The manual also recognizes the various interactions of materials, construction, equipment, and habitation, and the balance between the indoor environment, the building envelope, and the outdoor environment with its constantly changing temperature, humidity, and radiation.

The manual consists of four parts. Part 1, "Fundamentals," provides fundamental information and data relating to moisture control and the effects of moisture on buildings. Part 2, "Applications," discusses the application of related technologies to prevent or solve moisture problems in buildings. Part 3, "Construction Principles and Recommendations," gives guidelines and recommendations for designing and constructing new buildings and for increasing the moisture resistance of existing buildings. Part 4, "Implementation," provides insights into the various mechanisms for implementing moisture control strategies.

In Part 1, "Fundamentals," the theoretical basis of moisture control and applicable data is provided. Chapter 1 discusses the fundamentals of moisture transfer, condensation, and evaporation, and the appendix to the chapter is directed toward those with little or no knowledge of moisture transport mechanisms; the main body of Chapter 1 will be more useful to those with a good general understanding of the physical phenomena involved. Closely related to the first chapter is Chapter 2, which discusses the state of the art in computer programs for modeling the mechanisms discussed in Chapter 1. Chapters 3, 4, and 5 provide needed information and data on moisture-related properties of building materials and how their performance is affected by moisture. These chapters discuss building materials in general (Chapter 3), thermal insulations (Chapter 4), wood and wood products (Chapter 5). The last three chapters in Part 1 discuss: molds and other organisms in buildings and related health effects (Chapter 6); considerations of climate (Chapter 7), which includes needed tabular data for the United States, Canada, and other countries required for identifying climate zones and for use in calculations discussed in Chapters 1 and 11; and Moisture Sources (Chapter 8), which describes in both quantitative and qualitative form the major possible sources of moisture in buildings.

Part 2, "Applications," discusses the technologies that affect the moisture balance in buildings and the techniques used to determine the adequacy of materials, components, systems, and structures. Chapter 9 discusses the effect of ventilation and ventilation strategies both in cold and in warm and humid climates. Chapter 10 is devoted to issues of heating and cooling equipment and how they can be used to control moisture in buildings. In Chapter 11, several design tools for determining potential moisture effects on building components are discussed and their use demonstrated. Chapters 12 and 13 discuss the myriad of tests and measurement methods that can be used to determine material or component properties both in the field and in the laboratory (Chapter 12) and the techniques and methods used by investigators of moisture problems, including examples to demonstrate the use of test and evaluation methods (Chapter 13). An appendix to Chapter 13 also discusses statistical issues relating to the number of tests to perform and the degree of confidence a certain number of tests provides. The last chapter in Part 2, Chapter 14, provides a valuable compilation and discussion of many case studies conducted in this country and in Canada for determining the effect of moisture on constructions of actual buildings and to test various proposed standards designed to increase energy efficiency and moisture resistance. This chapter is useful in understanding the effect of climate on different building systems, components, and materials. The chapter will also be particularly helpful to those planning their own large-scale field studies. Because of a lack of major field studies and data on commercial and high-rise buildings, the chapter discusses only residential constructions.

Part 3, "Construction Principles and Recommendations," provides eight authors' recommendations for the design and construction of new moisture-resistant buildings and for upgrading existing buildings for greater moisture resistance or tolerance. The authors were carefully selected to provide a broad spectrum of the current state of the art, approaches, and solutions. Because of this, and because moisture control in buildings is still an immature science, still largely an art, the authors of these chapters do not necessarily agree with one another. Also, the guidelines are not ASTM recommendations, but present the authors' own understanding of the subject. Chapter 15 discusses the general concepts of moisture-resistant buildings. The chapter provides the traditional, generally accepted principles which apply to all buildings. Chapter 16 is devoted to roofing. Although it is recognized that roofing is the most important building component with regard to moisture control in buildings, roofing is discussed only in this chapter as it is recognized that roofing technology is well advanced and has its own broad and generally accessible literature. Chapter 17 discusses new residential construction. Chapters 18, 19, and 20 discuss new commercial and high-rise buildings (Chapter 18); existing residential buildings (Chapter 19), and existing commercial and high-rise buildings (Chapter 20). Because manufactured homes and historic buildings have unique moisture-related concerns, Chapters 21 and 22 were included to discuss these special building types.

Part 4 discusses implementation mechanisms. This section is organized along a simple concept: First, the building should be designed, built, and repaired according to contract documents which contain the principles outlined in the earlier sections and chapters. Second, codes and standards provide a firm basis for selecting products, systems, and construction features, and third, when all else fails, there are arbitration and court proceedings to resolve conflicts. The first three chapters of Part 4 follow these three phases. Chapter 23 explains the role of contract documents—specifications and drawings—in implementing moisture control strategies and provides guidelines for those not familiar with architectural design and production. Chapter 24 provides a useful compilation of standards and codes relevant to moisture control in buildings. Chapter 25 discusses legal aspects, illustrated by a real life case study. It was suggested above that moisture control in buildings is not currently treated as a separate design discipline and that it is the hope of the editor and the authors that this manual will contribute to the establishment of such a discipline. The last chapter of Part 4, Chapter 26, suggests, as a start towards such a discipline, a methodology for the design of moisture-resistant buildings modeled after the well-established methods used for structural design and analysis.

It is the policy of ASTM to require SI (metric) measurements in all its publications. Accordingly, all chapters use SI units in the text, and most chapters also provide common units in the text. Most tabular data are provided in only one measurement system. As a convenience to the reader, a metric conversion table is printed at the back of this book.

ASTM, the editor, and the individual chapter authors request comments on the usefulness, technical content, format, and any other issues related to the manual in its current form. We will strive to respond to all comments and to incorporate useful suggestions in any upcoming editions.

Heinz R. Trechsel
Editor

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PART 3: CONSTRUCTION PRINCIPLES AND RECOMMENDATIONS

PART 4: IMPLEMENTATION

Part 1: Fundamentals

Fundamentals of Transport and Storage of Moisture in Building Materials and Components

1

by Marinkal K. Kumaran,[1] Gintautas P. Mitalas,[1] and Mark T. Bomberg[1]

NOMENCLATURE

a_m	Moisture diffusivity, m^2/s
a_{mT}	Thermal moisture diffusivity, $m^2/(K \cdot s)$
c	Concentration, kg/m^3
J	Flux or density of flow, quantity/$(m^2 \cdot s)$
k	General transport coefficient
P	Air pressure, Pa
p	Partial pressure, Pa
p_v	Saturation vapor pressure, Pa
T	Temperature, K or °C
V	Volume, m^3
grad ϕ	General driving potential
λ	Thermal conductivity, $W/(m \cdot K)$
μ	Vapor permeability, $kg/(m \cdot Pa \cdot s)$
ρ	Density, kg/m^3

Subscripts

B	General entity transported
m	Moisture
Q	Heat
v	Vapor
X, Y, Z	Cartesian coordinates
0	Dry material

INTRODUCTION

WATER, WHICH IS ABUNDANT on our planet, constantly undergoes various physico-chemical processes and interacts with all living and nonliving organisms. As much as water is essential for all life forms, it can also cause deterioration and dissipation of many natural and man-made materials. Buildings constructed to last many decades consist of a large number of such materials. Hence, building researchers, designers, and practitioners have always been interested in the role of moisture in buildings, such as the degradation of the thermal performance of buildings.

Among questions one would like to answer to define the role of moisture in the built environment, the following three are crucial:

1. How can the transport of moisture through building materials and components be predicted?
2. How can the harmful accumulation of moisture in building materials and components be prevented?
3. How does moisture transport affect the energy efficiency of buildings?

To answer these and similar questions, one should be equipped with a detailed knowledge of the basic physics of moisture transport and storage, two fundamental phenomena that are interrelated in a rather complex way. Some of this knowledge has been provided by soil scientists [*1,2*]. Building materials can be treated as porous bodies, similar to soil, and the theory developed for describing soil water movement can be adapted for building applications [*3*]. However, an additional transport process, viz. air transport, not often considered by soil physicists, constantly interacts with heat and moisture transport processes in buildings and makes the physics of moisture transport in buildings more complex.

Over the past two decades various groups of building researchers have significantly improved analytical and experimental methods to determine the hygrothermal behavior of building materials and components as influenced by simultaneous heat, air, and moisture transport [*4*]. There are numerous technical publications in this area in the literature as listed in recent reviews [*5–7*]. Later chapters in this handbook deal with various aspects of hygrothermal behavior of building materials and components individually. This chapter is intended to summarize our present knowledge of moisture transport and storage in relation to building materials and components.

THE THERMODYNAMIC STATES OF MOISTURE

Water, like any other pure substance, can exist in three states: solid (ice), liquid (water), and gas (vapor). These three states of moisture may exist in buildings. In addition, the various building materials can capture water molecules from the surrounding air and localize them on their surfaces. Moisture so localized is said to be in an adsorbed state.

In the absence of other material, the equilibrium between solid, liquid, and vapor is well defined. At any given temperature there is a well-defined maximum vapor pressure that moisture can establish; this is called the saturation vapor pressure. There is only one temperature and saturation vapor

[1]Senior research officer, Building Performance Laboratory, Institute for Research in Construction, National Research Council Canada, Ottawa K1A 0R6.

pressure at which all three states can coexist. This is referred to as the triple point of water. The triple point temperature is 273.16 K, and the corresponding saturation vapor pressure is 611 Pa. At any other temperature, T, the following two vapor pressure equations give the saturation pressure, p_v, fairly accurately

$$p_v\ (\text{Pa}) = \exp\left(28.542 - 5869.9/T - 2882/T^{1.5}\right) \text{ for } 250\ \text{K} < T < 273.16\ \text{K} \quad (1)$$

and

$$p_v\ (\text{Pa}) = \exp\left(22.565 - 2377.1/T - 33\,623/T^{1.5}\right) \text{ for } 273.16\ \text{K} < T < 330\ \text{K} \quad (2)$$

The unique relation between saturation vapor pressure and temperature is the basis, as explained in the appendix to this chapter, for various psychrometric calculations in building applications.

But within the structure of a porous building material the above uniqueness between saturation vapor pressure and temperature does not exist. If a porous body is homogeneous and isotropic, it may have its own unique relation for the dependence of temperature and maximum vapor pressure. Such relations are virtually unknown because most building materials are nonhomogeneous and anisotropic. But in practice another property, considered to be representative of each porous building material, called sorption isotherm is indirectly used to supplement such relations.

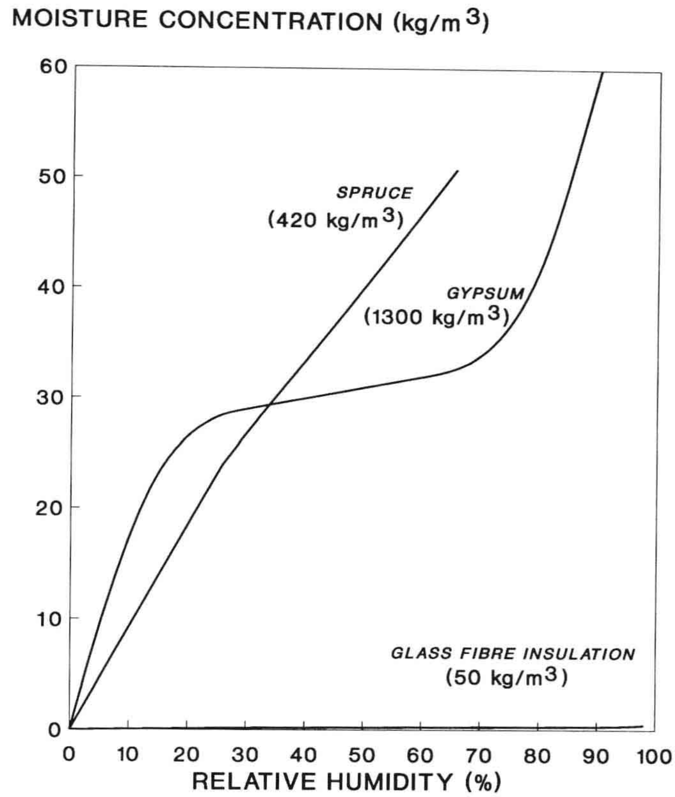

FIG. 1—Examples for sorption isotherms of common building materials. The quantities in brackets indicate approximate densities of the materials.

SORPTION, A MECHANISM FOR STORAGE OF MOISTURE

As mentioned above, solid surfaces in contact with water vapor have the tendency to capture and localize water molecules on them. This phenomenon is called adsorption. The maximum amount of moisture adsorbed by a given amount of solid depends on the temperature, the partial pressure of water vapor, and the surface area. Furthermore, each material has its own characteristic affinity towards water. This affinity is commonly referred to as hygroscopicity.

Let us consider the response of a homogeneous fibrous material to water vapor at a fixed temperature. If the surrounding air is perfectly dry, the amount of water adsorbed is zero. But as the vapor pressure is progressively increased the whole surface area of the fibers participates in providing a surface for water molecules to be adsorbed, first in the form of a monomolecular layer and then in multimolecular layers. This continues until the surface layers at various locations grow large enough to form droplets of water or frost particles. From the absolute dry state to this point of droplet or particle formation, the material is said to be in its hygroscopic range. In this range the maximum amount of adsorbed moisture is restricted by the hygroscopicity of the material. Once the vapor pressure is above this hygroscopic range, larger amounts of moisture begin to deposit in the pores until the structure is filled with condensed moisture. The maximum amount of moisture that can be accommodated by a material is limited only by its porosity. In principle this behavior seems well-defined, but in practice each specimen of building material has its own individual response to water vapor.

The relation between the amount of moisture adsorbed and the vapor pressure of moisture at a given temperature is called the *adsorption isotherm*. Naturally this relation is temperature dependent, but it is generally believed that if the adsorption isotherm is expressed in terms of relative humidity of the surrounding air, all the isotherms for a given material tend to merge into a single relation. This merged relation is called the *sorption isotherm*. Even though no unique sorption isotherm can be obtained for any building material, researchers have determined representative sorption isotherms for a variety of materials [*8*]. For example, let us consider three common building materials, viz. spruce, gypsum board, and glass fiber insulation. Figure 1 shows three representative sorption isotherms for the materials. If the pores of these materials are eventually filled with water, the volumetric water content in these materials can be as high as 800, 400, and 970 kg/m^3, respectively.

HYSTERESIS

The reverse of adsorption, namely desorption, presents further complexity. If a porous building material is saturated with water and allowed to dry in air at different relative humidities, it does not retrace the sorption isotherm. Usually, it retains more moisture during desorption than it can adsorb at any given relative humidity. This phenomenon, referred to as hysteresis, is illustrated in Fig. 2 with reference to gypsum board. Further examples may be found in Ref *8*.