Moisture Transfer Through Materials and Systems in Buildings


ABSTRACT When many of the current moisture control design guidelines for buildings were developed 50 years ago, they were consistent with analytical approaches and test methods. This consistency deteriorated when the importance of air convection was recognized. Although considerable research on moisture problems in buildings is available, there is no general consensus aimed at prevention. Sophisticated analytical moisture models have been developed, but they are not easily available or are too complex to use as analytical or design tools. Current water vapor transfer test methods do not provide material property data for these models or for design practice.

To restore consistency and make this information more useful to building practitioners, a coordinated approach to mathematical modeling is needed. Practical analytical tools need to be developed and test methods need to be expanded or developed to yield data appropriate for these models. Finally, more detailed information about airflow patterns in building components needs to be obtained.

KEY WORDS: moisture, materials, buildings, water vapor, test methods, modeling, condensation, ventilation, water vapor transmission, testing

Throughout the United States and Canada, moisture problems in buildings are a source of numerous complaints and owner dissatisfaction. Excess moisture occasionally leads to serious structural damage. Despite the importance and pervasiveness of moisture problems, our current understanding of the principles of moisture transfer in buildings and building components is incomplete. Reliable and practical methods to predict condensation and moisture damage in buildings are not available. Although a considerable amount of research has been done on moisture problems in buildings, relatively few firm, practical guidelines aimed at prevention have been developed. Existing guidelines are considered outdated and based on incomplete information, but there is no consensus among the experts to serve as a basis for new guidelines.

No lack of consensus existed in the 1930s and 1940s, when most of our current guidelines for moisture control were conceived and developed. The interpretation of condensation problems in existing buildings was consistent with the dewpoint design and analysis method, which is still widely in use. The test methods for permeability of materials, in turn, were compatible with the data requirements for the dewpoint analysis method and with the definition of vapor retarders, or vapor barriers as they were called then. This consistency among building practice, mathematical analysis, and standard test methods has deteriorated.

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This paper represents my interpretation of the current discrepancies and my views on the need for improved standard test methods and analytical tools.

Moisture Problems and Building Practice

Serious moisture damage in buildings is usually the result of a combination of unfortunate circumstances and design flaws. It often is a failure of the building as a system, not of any individual building material. Although many cases of moisture damage can be attributed to water leaking into the building envelope, other cases of moisture damage to walls, roofs, or foundations are complex and difficult to determine. In one such case, I took part in several site visits and in the formulation of recommendations for repair and preventive measures. Although this was an unusually serious case of moisture damage, it illustrates the premise that moisture damage is often the result of compounding factors. A large number of manufactured homes in Wisconsin and other midwestern states exemplified severe decay in the exterior walls. The decay in the walls resulted from winter condensation, which in turn was caused by the unfortunate combination of design details and high indoor humidity. The poorly installed interior vapor retarder with numerous penetrations did nothing to prevent the problem, and a heavy asphalt-coated building paper between the sheathing and the siding may have further exacerbated the problem by retarding the drying of the sheathing in the spring. However, high humidity was the main cause and we therefore recommended increased ventilation of the living space combined with repair of structural damage.

This recommendation contrasted sharply with traditional recommendations for moisture control. Many early design solutions and remedial measures to control moisture in buildings focused on control of vapor diffusion through the installation of vapor barriers (later called vapor retarders) [2–5]. A vapor retarder was defined as a material with a permeance of 1 perm or less. This approach seemed effective and generally accepted for many years and is still widely reflected in building codes and building practice. Until quite recently, recommendations for remedial moisture control in older homes without continuous vapor retarders focused on diffusion control by applying vapor retarder paints [6].

In the 1960s, the importance of air leakage began to emerge [7,8]. Observations and calculations made it clear that the amount of water vapor carried by air currents could be much larger than the amount delivered by diffusion. Little doubt remained that many of the condensation problems in buildings are associated with air leaks. This concept lead to design recommendations that focused primarily on airflow control, such as the Airtight Drywall Approach (ADA) [9]. The new Standard Practice for Selection of Air Flow Retarder (AFR) for Insulated Frame Building Walls, under development in ASTM Subcommittee E6.41, is an attempt to reconcile the current practice of controlling vapor diffusion (that is, with vapor retarders) with recommendations for airtightness. This new standard practice will provide useful and needed interim guidelines, but not enough is known at this time about the behavior of the system to make a conclusive recommendation about proper design. Mathematical models are needed to explore the behavior of different building designs under a variety of indoor and outdoor conditions. Such models would also allow us to evaluate the influence of new building materials and minimize the number of needed field tests.

Field studies of moisture in walls show that occasional condensation does not necessarily damage the structure or the materials [10–12]. It is possible and even likely that many buildings that seem to perform quite satisfactorily do experience limited condensation at one time or another. To formulate realistic performance criteria, we need to determine to

1 A perm is a unit of water vapor permeance and is defined as 5.7 \times 10^{-11} \text{ kg/Pa} \cdot \text{s} \cdot \text{m}^2 (1 \text{ grain/ h} \cdot \text{ft}^2 \cdot \text{in. Hg}).
what degree moisture can be allowed to accumulate. Once criteria are established, reliable and practical design methods must be developed so that builders can design building envelopes that meet these criteria. These design methods should be based on verified mathematical models, just as the current building energy design methods are based on verified mathematical models of building energy.

The satisfactory performance of a building and its components depends not only on design, workmanship, and materials, but also on the environmental conditions inside the building. In the past, design recommendations were specified by climate zone. Sustainable “safe” interior conditions have not been explicitly defined. The design of the building, especially of the exterior envelope, determines to a large extent its tolerance for extreme interior conditions. A well-insulated building with good control of airflows and vapor flows and thermally sound windows has more tolerance for high interior or exterior humidities than a building without these features. However, each design has its tolerance limits and it would be helpful to define these limits. Conversely, discussion of sustainable or desirable interior conditions should consider building design. Humidity levels recommended for human health and comfort sometimes exceed the tolerance limit of the building. In such a case, humidity needs to be maintained below those recommended levels, or the tolerance limit needs to be raised by changing the building envelope design. Unfortunately, these limits are largely unknown at this time. To determine the tolerance limits for different building design and climate combinations, we need practical and accurate simulation models.

In summary, to make better practical design recommendations for buildings and to better define performance criteria, realistic mathematical models are needed. These models should predict the moisture performance of the building envelope based on expected interior conditions, building design, and climate.

**Mathematical Models**

The earliest mathematical approaches to moisture movement in buildings were entirely based on water vapor diffusion. Early design recommendations were largely based on results from these mathematical models. When the importance of air convection was realized, these methods began to lose credibility, although several attempts were made to incorporate air convection and ventilation into these methods.

The complexity of moisture movement is perhaps the greatest obstacle to practical moisture modeling. Figure 1 illustrates the different transport mechanisms, phases, and storage modes. The traditional approach to building moisture analysis had focused only on diffusion of water vapor. As Fig. 1 shows, moisture movement involves many additional mechanisms and parameters. A brief explanation and overview of moisture transfer mechanisms follows.

Water exists and moves in several phases by many often simultaneous transport mechanisms. As water vapor, it moves by diffusion or convection. Diffusion takes place under the influence of a vapor concentration gradient and convection involves the movement of water vapor with airflows. In practice, movement by convection usually dominates.

Liquid water migrates by gravity, diffusion, and in porous materials, capillarity. Porous hygroscopic materials also adsorb moisture, and this moisture can move within the material in the adsorbed state. This movement has been termed transpiration. Transpiration dominates at high relative humidities with large amounts of adsorbed moisture.

Figure 1 does not fully reveal the complexity of moisture movement. Moisture in buildings often moves because of a temperature gradient. The moisture flow and heat flow are closely interdependent. In addition, heat is dissipated or released as moisture changes from one phase to another. To further complicate matters, the heat and moisture transfer coefficients

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often vary with moisture content and temperature. For example, it is well known that the thermal conductivity of wood changes considerably with moisture content [20].

Some mathematical models attempt to include all aspects of moisture movement. These models are based on detailed differential equations for simultaneous heat and moisture transfer. These equations were developed by Luikov [21] for multilayered wall constructions. However, these equations may often be simplified and tailored to specific moisture transfer problems. Depending on which simplifying assumptions are made and which parameters are considered the major driving forces, several alternative sets of equations can be formulated to describe moisture and heat flow. Bomberg [22] discusses several alternative approaches. Regardless of the form of the equations, the rigorous approach generally leads to a complex finite differencing or finite element model. There are several examples of such models [22-25].

The clear advantage of a model based on detailed differential equations is flexibility: the model generally handles a variety of moisture transfer situations. Complexity and large amounts of input requirements are the obvious drawbacks. Alternatively, moisture transport may be modeled on a macroscopic level by focusing on the building system instead of the individual building material. This requires a detailed knowledge of the behavior of the individual materials and components, but often significant simplifications can be made. The aggregation in such a model depends on the programmer's interest and the amount of flexibility desired. Of course, these models are limited in their application to the problem the model was designed to handle, but they are easier to use. One example of this approach is described by Cunningham [26-29]. The MADTARP program, developed at the Florida Solar Energy Center, incorporates both approaches. A detailed finite element model develops moisture transfer potential parameters that can be used at a more macroscopic level.
in the Moisture Absorption/Desorption Analysis Method (MAD) [30]. The MAD, in turn, can be used as part of a larger thermal and moisture building analysis program (MADTARP).

From this discussion, we see there are several existing models or models in development that can calculate with varying degrees of accuracy and detail moisture flows in buildings. However, their success in predicting moisture flows is commensurate with the accuracy of the parameter values in the model. Unfortunately, such data are often not available for common building materials. Current standard test methods for water vapor transmission (WVT) do not provide us with the data necessary for these models.

Many models of today exist only as a research tool and require considerable computational power. To become more useful as a design tool, they need to be simplified. Test methods for building materials that will yield moisture transfer properties suitable to these models are eventually needed.

Measurement Techniques and Test Methods

The original standard test method for water vapor transmission (WVT) of materials is ASTM Test Methods for Water Vapor Transmission of Materials (E 96-80) that was conceived in part to provide relevant material property data for the dewpoint moisture analysis method. It was therefore completely consistent with the analytical and practical approaches to moisture control in buildings at that time. Other WVT test methods developed later use different measurement techniques but suffer from similar limitations as ASTM E 96-80. ASTM E 96-80 is based on the concept of water vapor diffusion as the principal moisture movement mechanism. The permeance, calculated from the test results, is defined as moisture flux per unit of vapor pressure

\[
\text{Permeance} = \frac{WVT}{\Delta p}
\]

where

- \( WVT = \) water vapor transmission rate (g/h · m²), and
- \( \Delta p = \) vapor pressure difference (Pa).

Although the results are expressed in terms of vapor pressure differentials, the actual moisture transfer is more complex. As early as 1940, Babitt [37] stated that at high relative humidities the moisture transfer through hygroscopic materials was not directly proportional to the vapor pressure difference. Chang and Hutcheon [32] also recognized this, “Complications in the determination of permeabilities or permeances . . . arise from the use of simple flow equations. Much of the complexity of the actual functional relationship between flow rate, material properties, and the specimen environment, is thus thrown into the permeability coefficient.” They also recognized the effect of temperature gradients on moisture transfer. The permeance tests are conducted under isothermal conditions. Actual moisture transfer in buildings usually involves a temperature gradient. Data on the influence of temperature gradients are therefore needed for realistic models for moisture transfer in buildings. Results from the current test methods are difficult to apply to in-service conditions or to convert to parameter values needed for realistic models for moisture transfer. Determining WVT under a well-defined moisture and thermal gradient would be useful, but is difficult at best. The prospect for a nonisothermal WVT test method is being investigated by ASTM Subcommittee C16.31.

Until a new test method is developed, data from current WVT tests would be more useful if additional data were collected. Much would be gained if the moisture sorption charac-
teristics of the specimens would be determined along with WVT values. Sorption characteristics establish the relationship among vapor pressure, temperature, and moisture content of the material. In addition, the permeance should be established as a function of moisture content and temperature. If the permeability is known as a function of temperature and moisture content, the thermal moisture diffusivity may be estimated \([22]\). The approximate relationship of permeance with moisture content and temperature should be determined with measurements at minimally two different humidity conditions and temperatures. Thus, a minimum of four permeance values should be established, two wet-cup and two dry-cup. Preferably, more than four measurements at different temperatures and humidities should be done to determine the relationships with more precision.

One alternative to the permeance test has been described by Gaffner and Wilhelmsson \([33]\). This method, called the moment method, allows determination of the moisture diffusivity as a function of moisture content under isothermal conditions. A bar-shaped sample in a tube is placed on two supports, one of which rests on a precision balance (Fig. 2). The initial moisture contents at opposite ends are different, and moisture equalization is recorded as a change in weight with the precision balance. Diffusivity of different types of concrete have been successfully measured by this method.

Tests for water vapor transfer do not address transfer by convection, but moisture transfer by air convection is usually the most important mechanism in practice. The main problem in predicting convective moisture flow lies in the quantification of the airflows and their path. Relatively small airflows can deliver large quantities of water, especially when compared to other transfer mechanisms. Once airflows have been determined, the associated moisture transport is easily determined. Current pressurization techniques do not give us sufficiently accurate information about actual airflows under service conditions. More detailed measurements under service conditions and modeling are required to predict moisture transfer.

**Conclusions and Recommendations**

In the past, the approaches to moisture control in practice, mathematical analysis, and moisture transfer measurement focused on water vapor diffusion and were consistent with
each other. When the importance of air convection was recognized and sophisticated moisture models were developed, this compatibility was lost. A coordinated approach to modeling, measurement, and practice is needed. The following recommendations aim at restoring this consistency in approach and at making measurements and modeling more useful to building practitioners.

Mathematical models are crucial to the development of better practical guidelines for moisture design and remedial measures. However, current models are not readily available or are too complex to serve as a practical analysis and design tool. Simple mathematical models for moisture transfer in buildings need to be developed or derived from existing models.

Improved moisture transfer data must be collected on building materials for use in existing and future mathematical models.

Moisture transfer test methods need to be developed for determination of the influence of temperature gradient and moisture content on moisture transfer.

More quantitative information needs to be developed on airflows in building components. With this information, the associated moisture transport can be determined with relative ease.

References


