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A Conceptual System of Moisture Performance Analysis

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by Mark T. Bomberg[1] *and Cliff J. Shirtliffe*[1]

In a manual such as this one, individual aspects of moisture control are discussed in separate, discipline-oriented chapters, even though such a treatment of the subject matter does not allow the integration of these various aspects into a comprehensive strategy of moisture control. Yet, there is a need for consolidating the multitude of findings of the research and field studies in the rapidly developing science of environmental control in buildings. This chapter attempts to fill this need by introducing a conceptual system of moisture performance analysis.

Performance of whole buildings as it depends on building components, e.g., external envelope, mechanical and electrical systems, and operational conditions (defined by climate and occupancy of the building), must also be related to the selection of materials forming the components of the building system. In this process, the materials are selected on the basis of structural and environmental control considerations [*1*]. Yet, while the structural design is well defined, this is not the case with the environmental control process. In the worst case, the environmental design is based on experience gained by the designer in the trial and error process.

Heat, air, and moisture transport across a building envelope are inseparable phenomena. Each influences the other and is influenced by all the materials contained within the building envelope. Often we simplify the process of design by relating control of each phenomenon to a particular material or component. The thermal insulation, for example, is perceived to control heat transfer and the air barrier to control air leakage (Table 1). Likewise, the rain screen and vapor barrier eliminate ingress of moisture into the system.

While selected for one reason, these materials and components perform many different and interrelated functions and frequently contribute to several of the processes that control overall system performance. For instance, while controlling air leakage, an air barrier system [*2*] may also provide effective control of moisture flow. Similarly, by increasing temperature in the wall cavity, a thermal insulating sheathing may also reduce the degree of condensation in the cavity [*3*]. In the process of environmental control, the interactions between heat, air, and moisture transports must also be reviewed. And to ensure that all aspects of the building envelope perform effectively, we must deal with heat, air, and moisture transport collectively.

The primary function of the building envelope is to provide shelter from the outdoor environment and to enclose a comfortable indoor space. To do this, the envelope needs structural integrity and durability, particularly if it is to resist moisture damage. Of all environmental conditions, excessive moisture poses the biggest threat to integrity and durability, accounting for most of the damage in building envelopes. Many construction materials contain moisture, most notably, masonry or concrete. These materials demonstrate excellent performance characteristics as long as the moisture does not compromise the structural or physical integrity. However, excessive moisture jeopardizes both the material and its functionality.

When does a given moisture content become "excessive?" How do climate, operating conditions, and adjacent materials affect the wetting and drying of the materials? In designing for environmental control, professionals integrate two very different conceptual processes. One involves specific testing and analysis; the other encompasses broad qualitative assessments based on experience, judgment, and knowledge of what makes a building envelope function under a given set of conditions. On the analytical side is a complex array of tools, models, and data which describe the material, structural, and environmental factors relating to the building envelope. On the qualitative side is a sense of how a particular building envelope would function in that environment.

For example, a vapor barrier is typically classified at 1 perm (57 ng/m^2 Pa), a unit that for wood frame housing in given environmental conditions represents a sufficiently small flow of vapor flow. However, in calculations made for different regions of Canada using a complex model of heat, air, and moisture transport, barriers with permeance ranging from 0.1 to 10 perms could be found applicable [*4*].

So, despite the move to define vapor barriers by a precise measurements, the selection of the most appropriate environmental barrier involves both conceptual logic and mathematical analysis. Designers must still conduct an overall qualitative assessment to determine whether the barrier, chosen for its quantitative properties, would actually function in the specific application.

In this respect, there is a growing disparity [*5*] between the selection of traditional materials for typical buildings and rapidly changing characteristics of new materials. In the absence of data on their field performance, the moisture-related data on new materials and components must be developed through laboratory testing. But what information is needed? And what tests should be used to produce this information? There being, at the present time, no established design process relating to moisture control, this chapter postulates a concept of such a process, an integrated approach to

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TABLE 1—Environmental barriers and driving forces.[a]

Driving Force	Environmental Barrier	Design Feature
Vapor pressure	Vapor barrier	Vapor diffusion control
Wind pressure + rain	Pressure equalized rain (PER) screen	Eliminates wind pressure difference across rain screen
Rain	Air gap with weather barrier and flashings	Provides capillary break and leads water away
Groundwater	Dampproofing, gravel or crushed stone layer	Provides capillary break
Air pressures (wind loads, stack, etc.)	Air barrier (continuous airtight material and load support)	Carries wind loads to the desired location
Air pressure + high indoor humidity	Air barrier	Controls moisture flow via air leakage
Wind pressure difference	Weather barrier with load support	Eliminates effects of windwashing
Temperature difference	Thermal insulation	Reduces the rate of heat flow
High temperature, e.g., fire	Thermal barrier, e.g., drywall	Prevents rapid temperature rise on susceptible materials

[a]Note that in Table 1, in accordance with the *Oxford American Dictionary*, we use term barriers for all elements that control advance (retard) flows of heat, air, or moisture.

the development of moisture control strategies in buildings, modeled after a well-developed process of structural design.

APPROACH

The selection of materials for use in the building envelope is done by architects and designers. This selection is based on previous experience and the current information gathered during a number of successive design refinements, during which some aspects of the performance and the interaction of materials and systems are reviewed and revised accordingly. The knowledge gained on each application may be used in the later applications of the same system. This review of the design is informal, and its efficiency depends greatly on the experience with the particular construction system that the designer's team has. Often, when lacking experience with the particular construction system, the designer will produce a design that has not been optimized in terms of cost nor in the use of materials, especially newer materials.

A more rigorous approach is needed, where both material and system performance could be related to the specific climatic and service conditions that the envelope may experience. This analysis should involve computer-based analysis of moisture flow, air leakage, and temperature distribution in building elements and systems. The concept of such an approach to the design of moisture control in a building envelope and a building environment is presented in this chapter.

In developing a comprehensive moisture performance analysis, we shall use an analogy with the process of structural design, a concept introduced in the Scandinavian Moisture Research Program [6] and employed at Lund University [7–9]. The structural design process, Table 2, involves the following stages: selecting materials for the structural element, identifying the loads and mechanisms of load transfer, predicting the actual stresses and strains in the analyzed element, comparing these with the permissible levels of stress and deformation, verifying the material selection, and, when necessary, modifying the elements' dimensions. Structural design is a closed-loop process; it starts with a material and analyzes how well this material could perform a specified function in the system. In the structural design, all the system interactions are introduced into the load factors, and the dimensioning of the structure was achieved during one stage of calculations. Neither type nor dimensions of the material are likely to be modified at the later stage of the design.

This is not the case when designing moisture controls in the building system. As shown in Fig. 1, the interactions between heat, air, and moisture transfer phenomena lead to the situation where none of these design aspects may be analyzed in isolation from each other. A change in one aspect of design must be analyzed in terms of other aspects of climatic control. For instance, an increased thermal insulation that results in a change of heat flow rate may change the likelihood of inter-

TABLE 2—Pattern of structural design.

Stage of Analysis	Comments
1. Material pre-selection	Previous experience
2. Loads	Superposition, interaction
3. Mechanics of load transfer	Elastic regions
4. Predicted stress-strain	Worst case
5. Critical stress-strain	Safety factor, interactions
6. Material modification (dimensions)	Price versus property

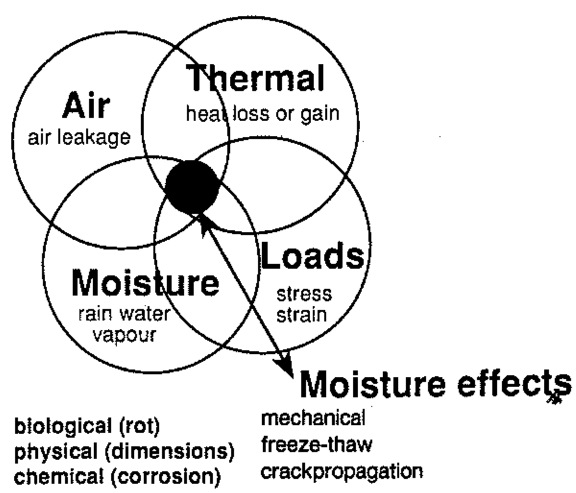

FIG. 1—Interaction between heat, air, and moisture transfer phenomena.

TABLE 3—Moisture performance analysis system.

Stage of Analysis	Comments
1. Material pre-selection	Preliminary selection
2. Moisture sources	Climate and use dependent Time dependent
3. Moisture transfer	Single-phase flows Multi-phase flow
4. Predicted moisture content	Time and space dependent Worst case scenario
5. Critical moisture content (cumulative exposure time)	Accessible porosity Total time of wetness
6. Material modification	Design modification

stitial vapor condensation, reduce drying potential of materials within the structure, etc. Thus, the design of moisture control may require performing multi-stage calculations (iterative loops). Nevertheless, within each of these iterative loops the structural analogy may be applied. Table 3 shows that iterative loops were comprised of the following stages:

1. Selecting materials for initial analysis.
2. Identifying the sources of moisture.
3. Identifying the types of moisture flows and interactions between heat, air, and moisture.
4. Predicting the distribution of moisture in the analyzed element at a given time.
5. Identifying the permissible level of the selected control parameters.
6. Modifying material selection.

The structural analogy concepts and the system of performance analysis [*10–15*] can be combined to produce a system of moisture performance analysis.

MOISTURE PERFORMANCE ANALYSIS

The system of moisture performance analysis requires the use of computational models to account for the effect of variable environmental conditions on moisture transfer through and moisture accumulation within the materials. From the distribution of moisture content in the material, as it varies with seasons of the year and length of service, one may determine if moisture content at any location exceeds the "critical" level of moisture associated with possible damage. The criteria for damage, called here "the limiting performance characteristics," are determined in independent laboratory experiments. The moisture performance analysis, as shown in Table 3, comprises six stages.

In the first stage of the analysis, one makes a preliminary material selection. This selection of material will be confirmed or modified in the process of further analysis.

In the second stage of the analysis, one identifies different sources of moisture. Some of these moisture sources depend on climatic conditions, e.g., rain or driving rain. Others depend on the service conditions and the design of the building element [*16*]. Some of the moisture sources occur only during the construction stage, e.g., construction moisture. Yet other sources may occur in a periodic fashion, such as drying from the surface of a material previously exposed to higher humidity [*17*].

In the third stage of the analysis, one identifies the main mechanisms of moisture transfer and selects a model for calculations [*18*]. A model based on single-phase moisture flows uses well-defined material characteristics such as vapor permeability or liquid conductivity, which, however, are difficult to measure [*19*]. A model based on multi-phase moisture flow is less elegant but uses material characteristics, such as moisture conductivity, that are easier to measure [*20–22*] (see Chapter 2).

Any model of moisture transfer must address three flows: heat, air, and moisture and their interactions. The need for simultaneous analysis of all three flows may be illustrated by a case of drying. The drying rate from the material surface is affected by many factors: temperature and moisture content at the surface, gradients of temperature and moisture content at the surface, infrared radiation to and from the surface, and air movement and mass transfer coefficient at the surface.

In the fourth stage of this analysis, one of two performance characteristics will be applied. These characteristics are moisture content (MC) and cumulative exposure time with respect to the specified effect (CET), i.e., the sum of the periods when moisture content exceeds the critical moisture content with respect to a specific effect of moisture.

The first characteristic, the moisture content, relates to those phenomena in which exceeding a specific level of moisture content under given temperature conditions is likely to result in immediate damage; for example, freezing a material initially saturated above a critical level will result in spalling or cracking of the material.

The second characteristic, cumulative exposure time, relates to all phenomena where a long-term exposure is involved in the deterioration process. In these cases, moisture may have insignificant impact on the short time basis (e.g., one or a few days); however, after many weeks, months, or years of exposure, these processes may result in a significant damage. Yet, as the long-term continuous exposure may have a different degree of severity than a series of intermittent exposures of the same total duration, both time and exposure severity factors must be considered.

The following concept of cumulative exposure time (CET) is proposed. CET is a sum of the interval of time when the actual moisture content is equal to or higher than the critical moisture content times the degree of severity of this exposure, namely

$$\text{CET} = \text{Sum}(I \cdot F_{ex}) \tag{1}$$

where I is the interval during which the actual moisture content is equal to or higher than the critical moisture content, and F_{ex} is the exposure severity factor.

The cumulative exposure time is needed for a number of moisture effects such as corrosion, mold growth, wood decay, or effect of moisture on thermal performance in all of which the degree of severity may vary with climatic conditions. For instance, corrosion of metals exposed to air occurs at different rates depending on temperature and humidity at the surface. The difference between the concept of "time of wetness" previously used in the durability research [*23*] and the "cumulative exposure time" introduced here is the presence of the factor F_{ex}.

The factor F_{ex} may vary between 0 and 1 depending on environmental conditions (temperature, moisture content, or relative humidity). For instance, a corrosion process may start, say at room temperature at 90% RH, but will proceed much faster at the same temperature and 98% RH (at this humidity even a small temperature variation can cause surface condensation that accelerates the corrosion process). Therefore, one could introduce a dependence of the factor F_{ex} on relative humidity, for instance, by postulating that $F_{ex} = 0$ at 90% and $F_{ex} = 1$ at 99.0%. The actual distribution of the F_{ex} factor, i.e., how it changes between values of 0 and 1 (linear, exponential, or stepwise) depends on the detailed knowledge of the deleterious effect of moisture. Not much is known at the present time how severity factors depend on temperature or humidity conditions. Making approximations, such as use of a linear dependence of F_{ex} on humidity, appears sufficient, since as shown by Becker [*15*] or Kashiwagi [*24*], there is a degree of latitude in use of weighing factors to evaluate performance of complex systems.

In the fifth stage of the analysis, the limiting levels of two performance characteristics discussed in the previous stage are identified. These limiting characteristics are termed "critical," namely

1. The critical moisture content (CMC).
2. The critical cumulative exposure time (CCET).

The first concept, CMC, implies that there is a point with a paramount significance for the analyzed effect of moisture. If the actual moisture content at any location of the material equals or exceeds the critical moisture content, CMC, there may be damage, i.e., the component may fail to maintain the required performance level or structural integrity.

The second concept, namely the critical cumulative exposure time, CCET, is defined as the total exposure time (i.e., the sum of intervals "*I*") determined under extreme conditions. It is equivalent to the period of reliable performance of the material (product) when the severity factor, defined in Eq 1, is one. Again, if, at any point in space and time, the actual value of CET exceeds the critical value, CCET, damage is expected.

Calculating cumulative exposure time provides a mechanism to evaluate effects of periodic or seasonal wetting and drying on materials and systems. In the above considerations, the severity factor describes a probability of the moisture damage. When the process is characterized by an "immediate damage," e.g., frost damage, a narrow range of moisture content brings probability of damage from a very low to a very high level (ascribed value of 1 for practical purposes). In case of cumulative processes such as mold, fungus growth, dimensional change, etc., probability of damage changes much slower with change in exposure conditions. When moisture content exceeds a critical value, the damage becomes probable (i.e., the severity factor becomes greater than zero). Yet, the process may take a long time before the product of time and severity factor reaches the critical value of CET.

In the sixth stage of the analysis, each of the two previously discussed performance characteristics, MC and CET, are compared with their limiting values, called the critical moisture content, with respect to the specified effect, or the critical cumulative exposure time, respectively. Comparing the predicted values of MC and CET with the critical levels (CMC and CCET) permits the use of performance analysis in moisture design.

On the level of material evaluation, these concepts assist in material selection. On the level of subsystem evaluation, these concepts help to modify the design since in each case the comparison between MC and CMC, or CET and CCET, becomes the basis for a decision in the design process.

AN EXAMPLE OF LIMITING MATERIAL PERFORMANCE CHARACTERISTICS

As previously discussed, a comparison between an actual performance characteristic such as moisture content or cumulative exposure period with the limiting value is the key element of the moisture performance analysis. As the calculation of the actual performance characteristics is discussed in many publications, notably in this manual, we deal with some of the limiting performance characteristics only.

Frost Durability

Frost durability of a material may be defined as its ability to withstand, without significant deterioration, the periods of freezing that actually occur throughout the whole period of service. This definition implies that frost durability is an environment-dependent property and that the same material may be durable under some field conditions but may be damaged under other conditions. Since the material must perform (be durable) under specific service conditions, one needs suitable means to examine the suitability of the material for the considered environment and to make a correct choice of material. Such means can be provided by moisture performance analysis where the moisture content of the material under actual service conditions is compared with its performance limits, i.e., CMC.

The concept of CMC with respect to freezing can be illustrated by reviewing the results of tests performed by Fagerlund [7] on two different types of clay bricks. Two cases shown above differ. While the critical degree of saturation was not reached during 240 h of water absorption for clay bricks shown in Fig. 2, the CMC is reached during 144 h of water absorption for material shown in Fig. 3.

Frost durability is represented here by the residual dynamic modulus, which is the dynamic Young's modulus divided by the modulus determined on the undisturbed specimen. Degree of saturation, *S*, is used on the other axis. The degree of saturation is the moisture content divided by the maximum that would be obtained if water has filled all the pores that are open and accessible for water ingress. The critical moisture content becomes in these notations the critical degree of saturation. The critical degree of saturation is the highest degree of saturation which may be found in a specimen without it being damaged under freezing.

Figures 2 and 3 show the stage when freeze-thaw cycling causes frost damage. The damage is characterized by a dramatic reduction in the residual dynamic modulus. Identical results are obtained with different numbers of freeze-thaw cycles or one-step freezing (noncycling simulation). Thus, the critical degree of saturation (representing critical moisture

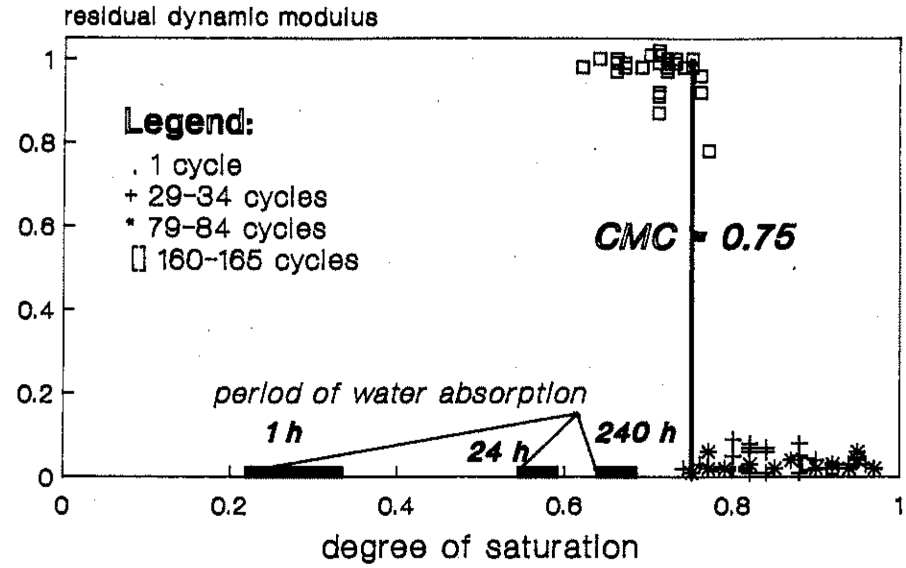

FIG. 2—Residual dynamic Young's modulus in freeze-thaw testing of a well-burnt clay brick with density 1860 kg/m³ versus degree of moisture saturation.

content) is independent of the test method. This fact implies that the concept of CMC may be used as a performance criterion for this type of material.

When evaluating frost durability of the material, one must consider temperature of the material. Only when temperature falls below the point at which pore water freezes (slightly below 0°C) and the actual degree of saturation S_{act} exceeds the critical degree of saturation, S_{crit}, can frost damage in the material be expected (Fig. 4).

In practice, one may ascribe a given threshold probability to a sub-zero temperature for a given period of the year. Any occurrence of S_{act} higher than S_{crit} during this period would become a criterion for possible frost damage.

The above example illustrates two stages in the process of evaluating the probability of frost damage in the material. First, one determines the critical degree of saturation (critical moisture content) for freezing. Then one compares it with the actual degree of saturation predicted from the model for the specified climate. If, during the period of sub-zero temperatures, the actual degree of saturation exceeds the critical one, one may expect frost damage in this material.

Let us now compare the proposed evaluation of frost durability with the traditional one. Traditionally, after being subjected to moisture ingress (absorption) under specific environmental conditions, the specimen is subjected to a freeze-thaw test. But the thawing part of the freeze-thaw cycle may

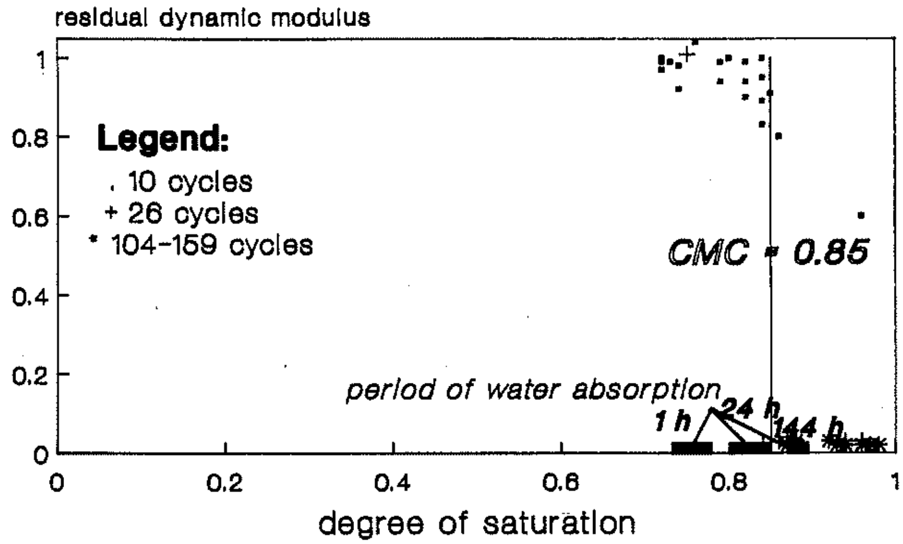

FIG. 3—Residual dynamic Young's modulus in freeze-thaw testing of an underburnt clay brick with density 1690 kg/m³ versus degree of moisture saturation.

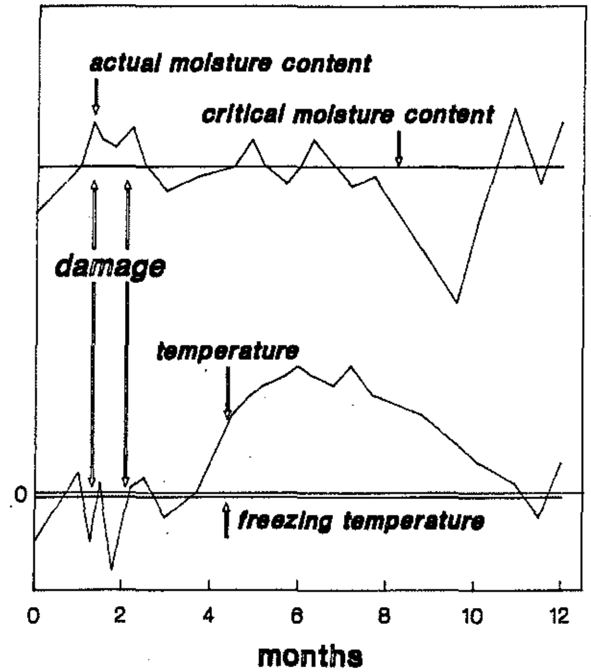

FIG. 4—Hypothetical curves of temperature and degree of actual saturation shown to highlight coincidence of conditions when frost damage is likely to occur.

also be used to stimulate moisture ingress into material. Such a test comprises cycling between two exposures, thawing in water (moisture ingress) and freezing in the air, for instance, ASTM Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666-90). In some cases, notably concrete, the degree of material saturation with moisture may increase with the duration of freeze-thaw cycling causing damage after a sufficiently large number of cycles. In other cases, the same conditions of freezing and thawing may not increase the degree of saturation at all. If the degree of saturation does not increase during the freeze-thaw cycling, one does not know whether this depends on a poor selection of the freeze-thaw conditions (conditions used for testing concrete may not be suitable for testing other materials) or on the nature of the tested material.

In addition to the critical degree of saturation defined by the means of residual dynamic modulus, Figs. 2 and 3 show results of isothermal water intake as a function of time (these clay bricks were immersed in water for different periods, e.g., 1, 24, 144, or 240 h). The short, thick line sections shown at the horizontal axis represent the degree of saturation attained during the water immersion test performed on several specimens. The degree of saturation for both types of clay bricks, S_{act}, increases with time of immersion.

What would be the outcome of a freezing test applied to these two clay bricks after they were immersed in water for a selected period, for instance 24 and 144 h. In the first case, both types of the clay bricks would be declared "frost durable"; in the second case (144 h of water absorption prior to the freeze-thaw test), the clay bricks shown in Fig. 2 would be thought "durable," but those in Fig. 3 would not. Would this mean that the clay bricks shown in Fig. 2 are durable under field conditions?

Actual moisture content depends on a balance between wetting and drying of the material in the building envelope and cannot be approximated by an arbitrary procedure such as a day or even a week-long immersion in water. While the worst-case scenario could be approximated by such a procedure, it requires, however, a check if the moisture accumulation under different conditions of wetting (e.g., condensation of thermally driven vapor) would exceed that obtained under water immersion, see Bomberg [25].

MOISTURE PERFORMANCE EVALUATION AND THE DESIGN PROCESS

Heat losses or gains, air leakage, and moisture transfer are influenced by the characteristics of all materials contained within the building element. Material selection must therefore be among the considerations given to the whole system. It implies that the moisture performance analysis must be performed as several iterations on different levels of construction hierarchy. (The concept of hierarchy was introduced in the performance analysis [10] to link different levels of consideration starting from the micro-structures and going through materials, products, and elements up to the construction systems.)

Is this iterative process of moisture performance evaluation compatible with a typical architectural design procedure? The answer is yes—both processes are very similar. The moment an architect, intentionally or not, starts to modify a "proven" design, the success of the final design is largely dependent on the type of questions that members of the design team raise and the answers they receive. In discussing design procedure, Strelka [26] stated that: "It also requires a willingness to change not only minor details, but the basic design itself, if the feedback information indicates that this is desirable. To do this necessitates that the design be kept as flexible as possible until the consequences of any design proposal are fully reviewed."

To compare the architectural design process with that of moisture performance analysis, we review the design of an air barrier in the exterior wall. In this example, as discussed by Strelka [26], the information flow starts with a search for suitable materials. Typical questions that are asked about air barrier materials are about their ability to be extended, about pliability, adhesion, means of attachment, connection, support, aging (change of material characteristics with time), weathering, and repairs. After developing an initial design, the designer addresses all intersections and joints between building elements (foundation-wall, wall-floor, wall-roof, wall-wall, wall-windows, and doors). To expect satisfactory performance in these details, the designer must continue to ask questions on the performance of the whole system: What rate of air leakage is permitted? Does the leakage occur in one place? How imperative is energy control? How critical is risk of drafts? Several iterations in design may be required until the answers to all these questions indicate that the designed element will have a satisfactory performance.

This example illustrates that after the preliminary material

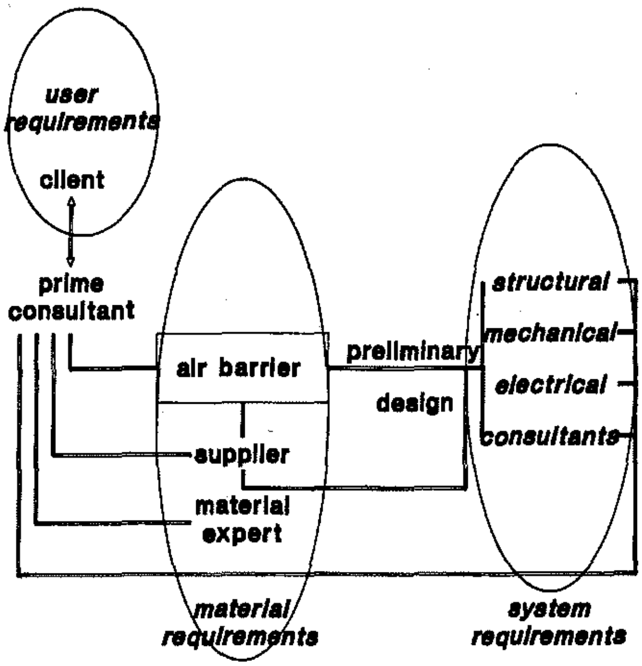

FIG. 5—Flow of information during design of air barrier (see text).

selection is completed the designer performs an analysis of its performance. Such analysis continues, and the next information loop includes the review of preliminary design with the structural, electrical, and mechanical consultants (Fig. 5).

The primary consultant must then review buildability aspects such as material installation under different weather conditions, degree of needed labor skills, and construction tolerances. This review must also address the long-term performance under service conditions: aging of the materials, stress and deformations during service, projected cost of repairs, and maintenance. At any stage, the design may have to be modified, a new material selected, and the process repeated.

As shown in the above example, the designer or the prime consultant is always performing a sort of performance evaluation. So, how is this analysis affecting the design process?

Application of moisture performance analysis introduces two new aspects:

1. It becomes a formal and recognized part of the design considerations.
2. It introduces a framework of organized procedures enforcing a review of specific performance aspects and replacing ad hoc questions or assumptions.

Figure 6 illustrates the interactive character of the design process performed stepwise in a number of iterative loops.

As the professional judgment involves experience gained when evaluating the field performance of similar construction systems, the evaluation process comprises the review of field performance of similar systems (combined with review of architectural details in the proposed system and assessment of their buildability), the review of laboratory tests on materials, or mock-up tests on components as well as predic-

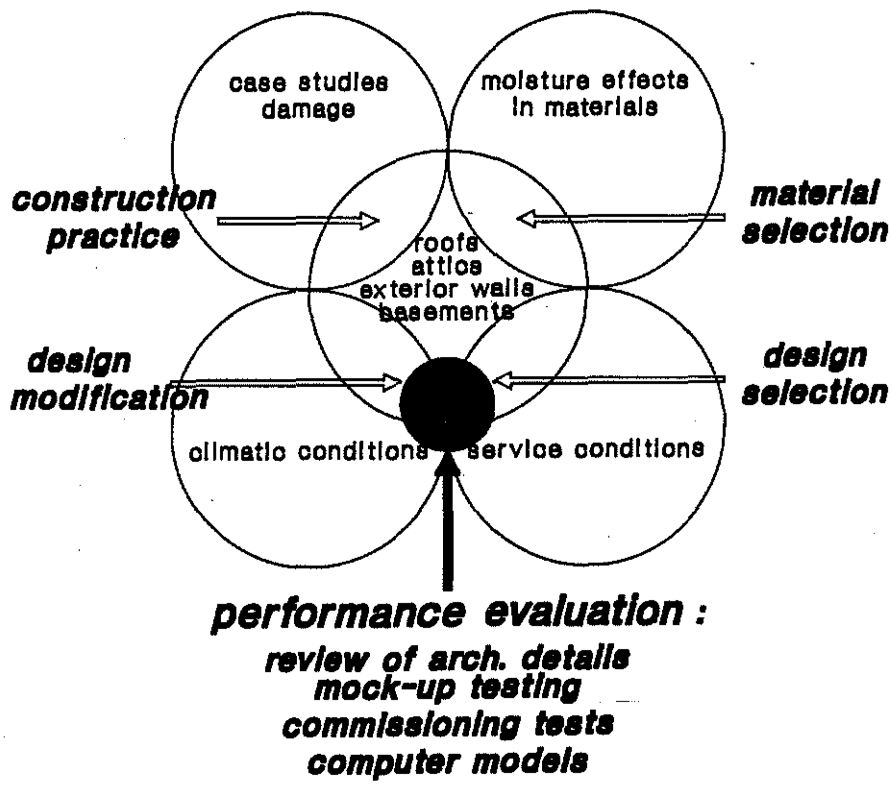

FIG. 6—Evaluation of performance on the level of building element and system.

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