Fundamental considerations in the design of exterior walls for buildings

Hutcheon, N. B.

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N. B. HUTCHEON

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FUNDAMENTAL CONSIDERATIONS IN THE DESIGN OF EXTERIOR WALLS FOR BUILDINGS

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The design of the exterior walls for buildings has been, and still is to a large extent, based on building practice as contrasted with what may be called building science. Changes have been slow, and in the main have come about through an evolutionary process of trial and error. Building practice has been fundamentally an inheritance from the past, modified by contemporary factors such as climate, economy, social habits, local aesthetic values, and local resources of materials and skills. The evolutionary process works slowly under the influence of new factors, and is equally slow in rejecting the obsolete.

The growth of scientific knowledge has led to great advances in the analysis and rational design of the purely structural functions of a building. There has been a great deal of development also in individual materials and components. There have been relatively small advances as yet in dealing adequately with all the combinations of elements, and with the complex inter-relations of phenomena involved in the performance of a complete building. The reasons are not too hard to find. It will be sufficient to note that, even now, contemporary building design draws upon the knowledge and experience of almost every branch of engineering science.

We have long since passed the point where we are content to rely on the "trial by use" method of assessing changes in design, materials and construction. Many new and interesting articles, materials, and proposed systems and methods of design and construction are offered each year. Those responsible for assessing and screening such new developments, realize only too well the relative inadequacy of our present knowledge of the suitability in any given case.

In addition, our standards of performance are continually being raised. As we reduce our major difficulties in turn, minor ones assume greater relative proportions, and we clamour for their reduction or elimination also, in the name of progress. The existing state of knowledge appears less and less adequate as the demands upon it increase.

Function of Exterior Walls

The function of exterior walls is to assist, together with floors and roofs, in the enclosure of space, in such a way that some or all of the physical environmental conditions, either inside or outside the enclosed space, can be regulated within acceptable limits. Physical environment must be regarded in the broadest sense, to include not only weather factors such as temperature, air movement, humidity, rain, snow and light, but also dust, odours, noise, and perhaps even now, nuclear radiation. Some thought will show that control of physical environment may include consideration of all forms of energy, and of all forms of matter which can occur in space.

Environment implies a subject, or subjects, which may be living plants and animals, including humans, or may be inanimate materials such as goods in process or in storage. The space either inside or outside a building may be occupied by any or all of these. A building is normally used for the control of the physical environment in the enclosed space, but it may also be used to contain or control substances, organisms or radiation, which might otherwise become a nuisance or a hazard in the space outside the building.

Consideration of the broad function of exterior walls serves two purposes; it emphasizes the range of considerations which may be involved in establishing the specific functional requirements in any given case. It serves also as a background for a logical approach to more practical discussions of wall design. An exterior wall may be regarded as a large membrane separating indoor and outdoor environment.

In fulfilling this function it must possess adequate strength and rigidity, with these requirements varying with the extent to which the wall must contribute to the overall structural strength and rigidity of the building. If there are no significant differences between indoor and outdoor environment a wall may be unnecessary. It is important to note that a wall may be subjected to variations at times from one side to the other of almost all the factors which go to make up physical environment.

The differences in these factors represent the use which is being made of the wall. The differences which it is desired to maintain will determine the properties the wall must have. The variation in the magnitude of the conditions throughout a wall from time to time will determine the conditions under which the materials making up the wall must function.

Environmental factors can originate within and on the wall itself as a result of matter and energy transformations. The materials in a wall may, for example, provide a source of odour or of undesirable gases indoors which are not found outdoors. Radiant energy may be absorbed by a wall and transmitted as heat. Water in liquid form may enter the outside of a wall and be transformed by changes in temperature, and with the uptake of heat, into vapour.

Similarly, water vapour originating either indoors or outdoors may enter a wall and be condensed to liquid or to ice within the wall. Wind blowing on the outside of a structure may produce vibrations which give rise to noise within the structure. Mechanical disturbances at one point may cause vibrations and noise at some distant point. Such transformations create many problems, since the possibility of their occurrence is frequently difficult to predict.

Major Considerations

A list of all the possible specific requirements of walls might be of little value. Many items in such a list would apply only in special cases. The majority of the items would not be provided for intentionally in most designs, but would be satisfied incidentally.

The major considerations which should be recognized in the design of walls for Canadian conditions are as follows:

1. Strength and rigidity.
2. Control of heat flow.
3. Control of air flow.
4. Control of water vapour flow.
5. Control of liquid water movement.
6. Stability and durability of materials.
7. Fire.
8. Aesthetic considerations,
9. Cost.

Strength and rigidity of building components have been studied by engineers for more than a century. While there are still many gaps in our knowledge and in our ability to predict, the phenomena involved are well recognized. No elaboration of them is needed, nor is it necessary to emphasize the importance of strength and rigidity in wall design.

Flow Control

All flows of mass and of energy have certain fundamental aspects in common. The movement of heat represents an energy flow, while air and moisture movement represent mass flow. Flow takes place due to potential differences, at a rate dependent on the potential difference and on the resistance offered to flow by the medium, in this case the wall.

An analogy with the well-known relationship between current, voltage and resistance in the flow of electricity may be drawn, although in some cases the equations may not be so simple. The potential is temperature in the case of heat flow, and air pressure and vapour pressure respectively in the flow of air and vapour. The potential in the case of liquid water movement may not always be readily identified.

All engineers will recognize the obvious possibilities of hydrostatic head, pressure and gravity forces. Liquid water can also be caused to migrate under electrical, thermal, and chemical forces, as well as by surface tension or capillary forces. The general situation in all cases may be described as a tendency for flow from a position or condition of higher potential to one of lower potential. The net result is a tendency to equalization of the potentials.

The flows of heat, moisture and air in walls have implications not only by themselves, but for all the other considerations listed. Air merits major consideration mainly because of its influence on heat and moisture flow. The overall transmission of heat, air and moisture through a wall can affect the ease with which the desired environmental conditions may be maintained, and so may have a marked influence on cost of operation of a building.

Temperature, and temperature change with the associated heat flow, together with moisture, are important factors in the deterioration of almost all materials. These deteriorating effects can and frequently do occur in walls. Such deterioration may interfere with the proper functioning of the wall if allowed to progress, or may result in high maintenance costs if materials have to be replaced or restored.

The temperature and moisture conditions imposed on the materials making up a wall can only be predicted through a knowledge of the overall conditions imposed on the wall, and of the nature of heat and moisture flow within a wall. This in turn requires a knowledge of heat and moisture flow in individual materials, and of how the overall flows in the wall will be affected by the type and arrangement of materials.

Stability

Stability of materials has been

included with durability, as a major consideration, rather than with strength and rigidity. Some effects of dimensional change due to temperature, and to creep and shrinkage in materials, are taken into account in assessment of strength and rigidity of walls, yet there are many cases of dimensional change which are more properly associated with considerations of durability.

The action of a bi-metallic strip, for example, under a change in temperature is well-known. Consideration is not always given, however, to the possibility that two materials fastened together in a wall and subjected to a change in temperature will expand differently, and if free to do so will take on a warped or changed shape. A similar condition can be produced by a temperature gradient maintained across a uniform material.

Some materials used in walls change markedly in dimension with change in moisture content, and effects similar to those described for temperature change and temperature gradient may result. If the wall elements or combinations of them are free to expand, little or no stress may be induced. When such tendencies to change in dimension are resisted, temperature stresses, and "moisture" stresses are produced. Frequently stresses are relieved by localized failure, such as cracking or tearing.

All materials exhibit some expansion due to temperature, while almost all non-metallic materials exhibit moisture expansion on an increase in moisture content. Moisture expansion is not confined to cases where contact with liquid water occurs, since most natural organic materials are hygroscopic and may absorb substantial amounts of water from the air, roughly in proportion to relative humidity.

Durability

Ability to resist destruction by freezing and wetting combined may be an important durability consideration for a material. When thoroughly saturated, good grades of both stone and concrete can be fractured in a single freezing (1). Under less severe wetting conditions concrete, stone and brick can be rendered unserviceable by repeated freeze-thaw cycles (1) (2).

While the conditions under which a material can become highly saturated in practice, and the destructive mechanism of freezing are not well understood, it is generally conceded that the destructive force is associated with the expansion of water on changing to its solid form at or below 32°F. Some complication is introduced by the fact that water may be super-cooled under certain conditions. Water held in a material may freeze at a temperature lower than normal, or may not freeze at all (2) (3).

Materials which must possess durability to freeze-thaw action are of course those used under conditions where both wetting and freezing will occur. The conditions under which the material is used are extremely important in determining whether the moisture conditions at the time of freezing will be serious. Examples of spalling brickwork will be found in most areas in Canada which have both high precipitation and freezing conditions, and where certain types of paint have been applied to the exterior.

A particularly troublesome class of durability consideration is that involved in change of properties of a material, brought about by the association of certain materials in a wall. Aluminum for example, is susceptible to attack by alkalis.

(1) Numbers in parentheses refer to items in the bibliography.

Cases are known where aluminum conduit used in concrete slabs, in which calcium chloride had been used were attacked chemically, producing a corrosion product of increased volume, so that the slabs were either cracked or caused to spall.

Fire Hazard

The inclusion of fire, or fire hazard, as a major design consideration will not be questioned. Several factors associated with the severe winter conditions combine to give it special importance, for example:

1. Extensive use of wood.
2. Substantial amount of heating required in winter.
3. Low indoor humidities which result in dry materials.
4. Increased difficulty of providing fire fighting services.

The extensive use of wood comes about not only because of the cost advantage, but also because of its low thermal conductivity in relation to strength, which gives it a unique advantage for certain uses in walls for cold weather conditions.

A fire hazard presented by one building is seldom confined to that building, and it is in the public interest to impose many restrictions by way of building by-laws. These mandatory requirements will frequently affect the ease with which almost all the other major requirements can be met in a particular design, and may begin to affect the public interest in another direction. Responsibility is shifted to the legislating authorities and their advisors, to see to it that the regulations imposed are technically sound, and do in fact achieve their purpose at reasonable cost. This applies equally to other regulations than those dealing with fire, but particularly to those which may of necessity have to be based on limited empirical data.

There is no adequate overall basis as yet for assessment of fire hazard. Studies in this field are peculiarly difficult. All the complicated mechanisms of heat and of air movement by convection occurring at ordinary temperatures in buildings, occur in exaggerated form at the high temperatures in a fire. Heat affects all the materials involved. The situation is made still more difficult by the highly transient nature of a building fire, and by the influence of scale or size. Experimental studies are costly when carried out on an empirical basis in large scale.

Aesthetic considerations, although of major importance in many designs, need not be discussed here, except to note that both inside and outside appearance may require consideration.

Annual Cost

The rational cost basis for assessment of the design excellence is the yearly cost, made up of the yearly cost of the initial capital outlay, operating cost, and maintenance and depreciation. All of these are peculiarly involved in wall design. The total yearly cost will determine the refinement to be attempted in the final solution to the design problem.

Beyond this, capital outlay can be reduced at the expense of increased operating and maintenance costs. The omission of insulation, for example, will decrease the capital outlay at the expense of increased operating cost. Increased cost of materials possessing superior properties can be offset by reduced maintenance and depreciation cost. The designer is not normally in a position to evaluate cost factors accurately in wall design.

Available technical knowledge will seldom be adequate for accurate prediction of service conditions and of performance, even when technical data on specific materials are available. It may be difficult or impossible, also, to assess many features of the functional excellence in terms of a cost criterion, particularly with regard to such things as comfort, and appearance. In spite of this, cost remains the basic directing factor in design.

Temperature and Heat Flow in Walls

The equivalent of about 20 million tons of coal per year, or about 26 per cent of the total national energy consumption is used for space heating in Canada ([4]). The thermal properties of walls used for all buildings to be heated are therefore a matter of some importance. The primary interest in heat flow through walls arises from the economics of building heating during the winter months, with the problem of heat gain in summer assuming a less important role.

Calculation of heat transfer through walls follows well established procedures involving the assumption of a uni-directional, steady-state, heat flow condition. The overall coefficient of heat transfer, U, can be calculated using accepted coefficients for the individual wall elements, with sufficient accuracy for establishing the size of the heating system required.

The temperatures throughout the wall for a particular set of conditions can likewise be calculated on the basis of the same simple theory. For wood frame walls these methods can be seriously in error for the prediction of wall surface temperatures, particularly when air spaces exist in the wall ([5]). The overall coefficient of heat transfer, U, for the average uninsulated wood frame wall with 2-in. by 4-in. studding, will be about 0.25 B.t.u. per sq. ft. per hour per degree temperature difference across the wall. Most simple masonry constructions without added insulation will have U values considerably higher than this.

Most walls used for houses are now constructed with added insulation, bringing the U value to 0.15 or less. The use of at least two inches of mineral wool insulation, or its equivalent, has been shown to provide the greatest reduction in yearly cost for wood frame walls ([6]). It is now common practice to provide similar amounts of insulation between 2-in. strapping on the inside of masonry walls used in house construction.

Temperature distributions and U values calculated by the usual methods for extreme winter and summer conditions are shown in Figs. 1, 2 and 3 for a plain concrete wall 8 in. thick, for the same wall with 2 in. of insulation added to the inside, and for 2 in. of insulation added to the outside. The effectiveness of the insulation in reducing the overall heat transfer, and in raising the inside surface temperature may be noted. Insulation therefore improves comfort conditions, and permits higher indoor humidities without the occurrence of surface condensation.

Insulation

The use of insulation in walls of commercial and industrial buildings has not been so widespread as in houses. This is due partly to the complications in introducing insulation into the usual "permanent" type wall construction. It is also due to the reduced surface-to-volume ratio in larger buildings, which reduces the heating cost per cubic foot of space, and makes a higher heat loss per square foot of wall somewhat less of a problem. In many industrial buildings high humidities must be carried for manufacturing and process work. Here the use of insulation becomes necessary to prevent surface condensation.

Insulation applied to a wall results in changed temperatures throughout the wall, with temperatures on the warm side of the insulation being raised, and those on the cold side being lowered. Unless the materials on the warm side are capable of restricting the flow of water vapour to the colder parts of the wall, condensation will occur, producing a troublesome and serious wetting condition within the wall.

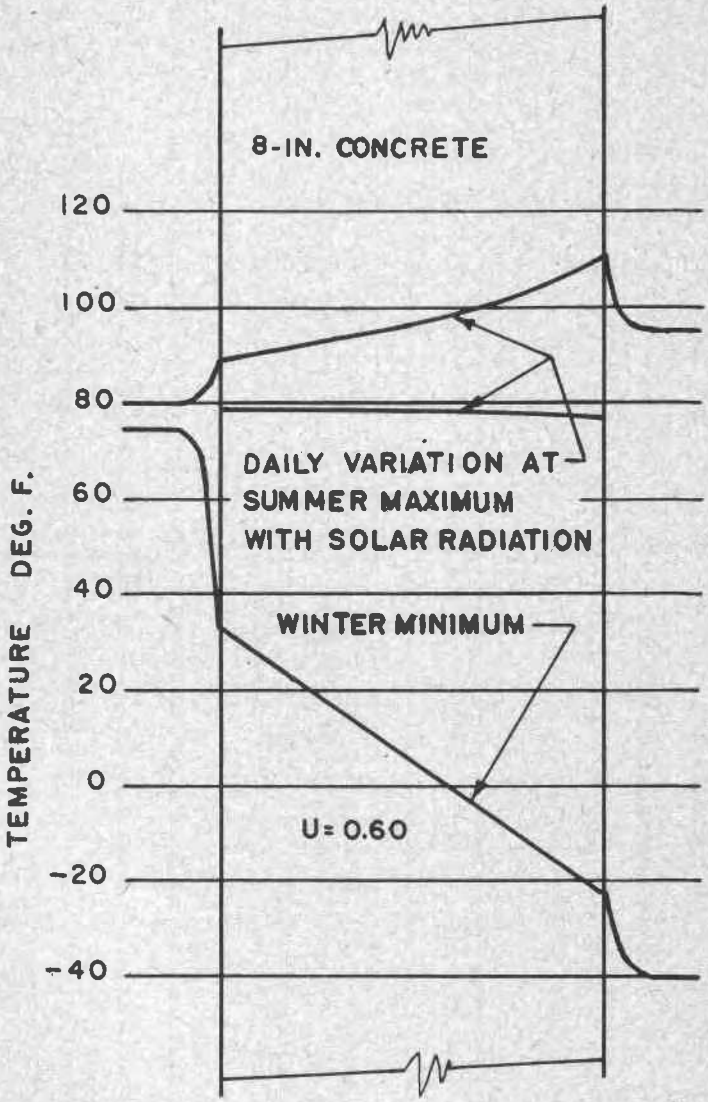

Fig. 1—Yearly temperature range throughout a plain concrete wall for air temperature range −40° to +95°.

It becomes necessary to consider carefully the question of control of vapour flow, which can be achieved by the incorporation of a suitable vapour barrier on the warm side of the wall.

Under summer conditions the heat flow is reversed, for part of each day at least, and flow occurs towards the inside of the wall. The calculation of this condition becomes complicated, since solar radiation absorbed on the outside raises the surface temperature, and produces a cyclical variation in temperature requiring more involved methods of calculation.

Solar Heat

The maximum solar energy received at the earth's surface has a heat equivalent somewhat greater per square foot measured normal to the sun's rays than the heat given off by one square foot of steam

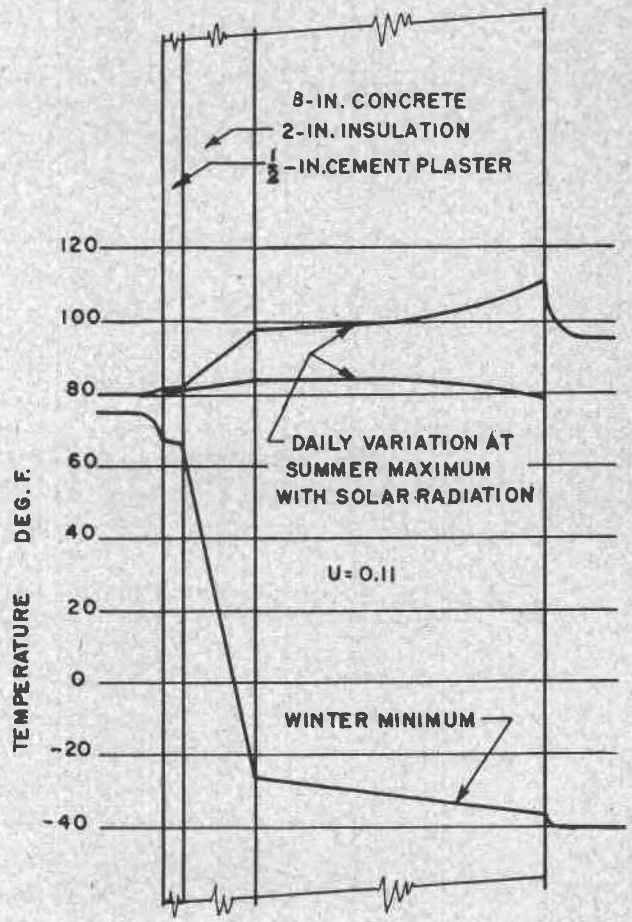

Fig. 2—Yearly temperature range throughout a concrete wall insulated on the inside, for air temperature range −40° to +95°.

radiator. The solar energy falling on a wall varies with the orientation of the wall, with the position on the earth's surface and with the time of day and time of year. Of the energy falling on a wall surface, from 40 to 90 per cent is absorbed, depending on the colour of the wall, and is converted to heat, the remainder of the solar energy being reflected.

The solar energy gain may conveniently be expressed as an equivalent air temperature, called the sol-air temperature, which without sunshine would produce the same heat gain at the wall surface. The sol-air temperatures for a dark coloured south wall at 40° latitude are shown in Fig. 4, as given in the 1952 Guide of the American Society of Heating and Ventilating Engineers. These have been based on the assumed air temperatures also

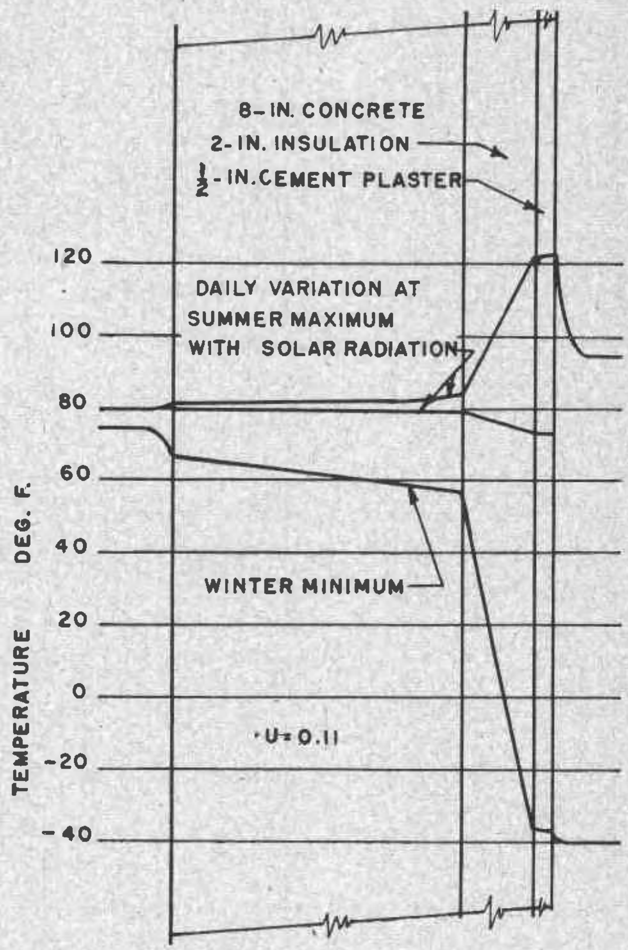

Fig. 3—Yearly temperature range throughout a concrete wall insulated on the outside, for air temperature range −40° to +95°.

shown, and will be similar to the values for a wall of medium colour at 50° N. latitude.

The periodic heat flow condition has been worked out by Schmidt's graphical method (7) to show the approximate temperature variations throughout the day. These are presented in Figs. 5, 6 and 7 for the same three walls previously used. Under periodic heat flow conditions, the temperature wave reaches the inside of the wall, considerably reduced in amplitude, some con-

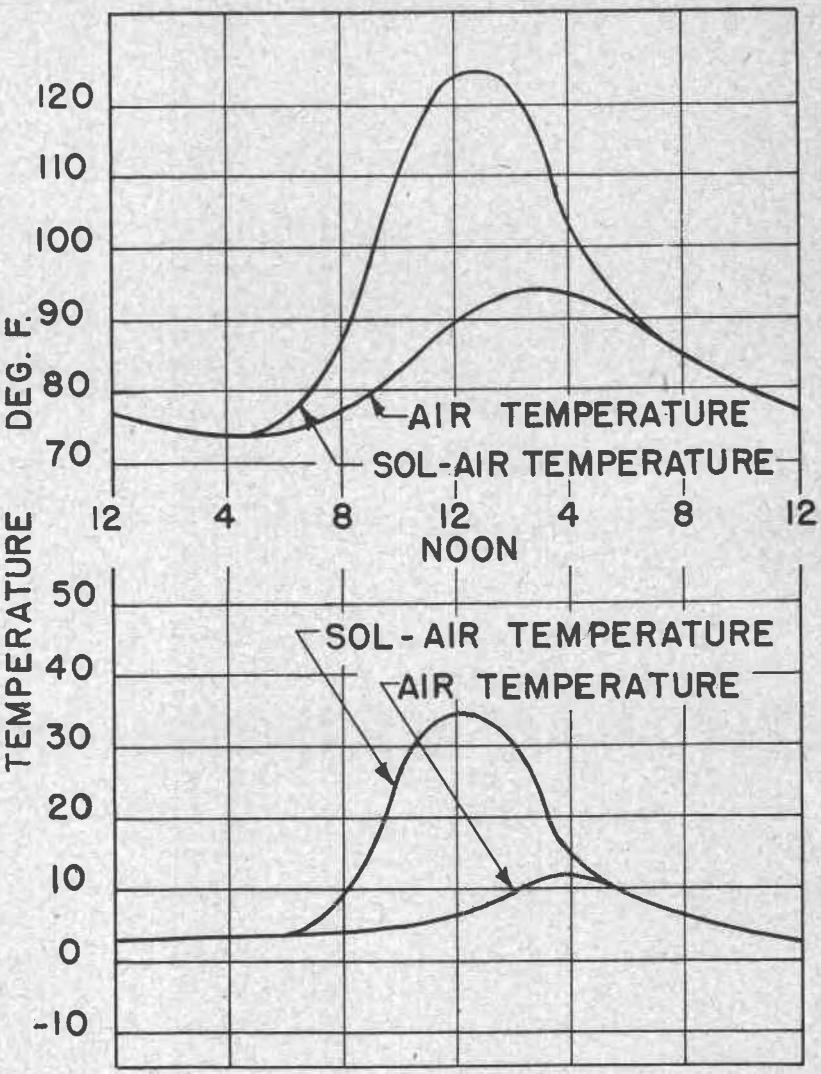

Fig. 4—Air temperatures and sol-air temperatures for a dark wall at 40°N. latitude on a summer day, and for a medium coloured wall at 52° N. latitude on a winter day.

siderable time after it is imposed on the outside. This characteristic lag is brought about by the heat storage capacity of the wall, and is seen to be about five hours for the plain concrete wall.

The addition of 2-in. mineral wool insulation increases the lag by another two hours. The solar heat gain on the outside of the wall reaches a peak at 1 p.m. while the maximum rate of heat transfer

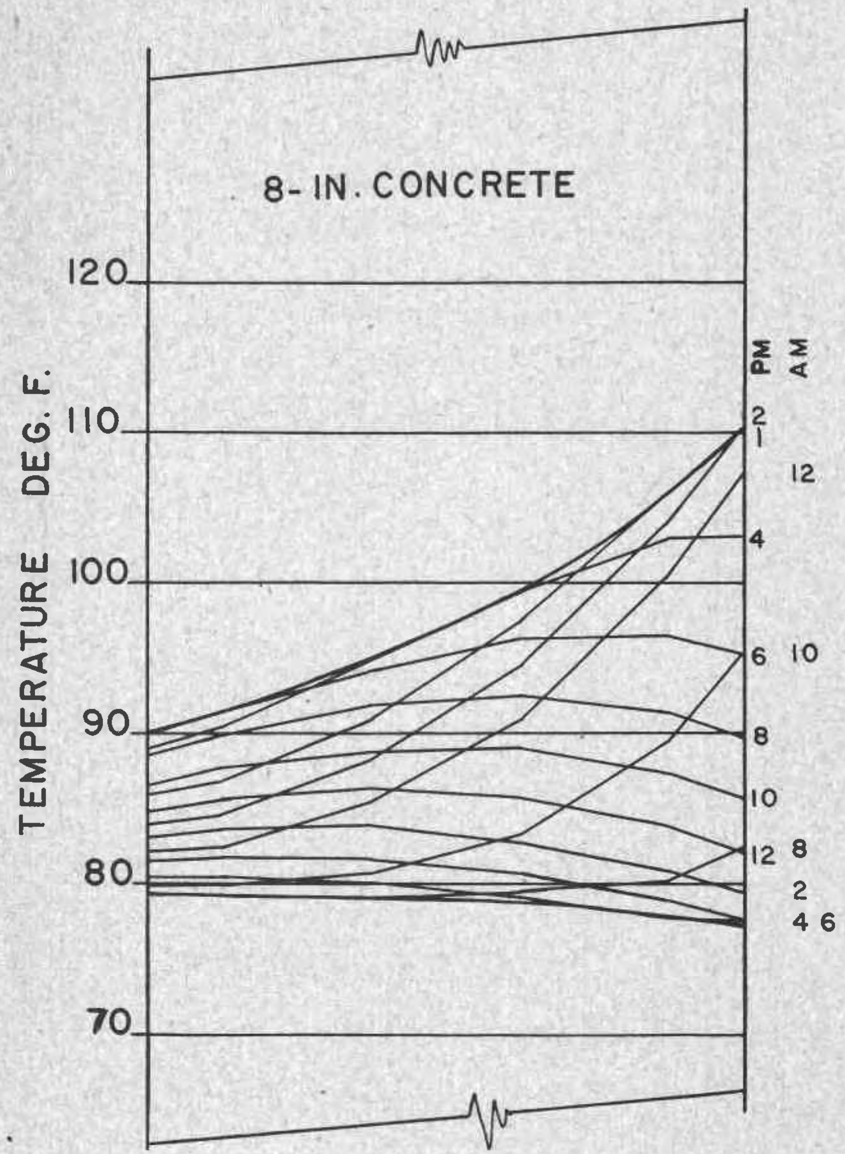

Fig. 5—Variation of temperature with time in an 8-in. plain concrete wall due to solar radiation in summer.

from the inside of the wall to the space occurs from five to seven hours later. It will be noted that after 4 p.m. heat is flowing from the centre of the wall to the surface in both directions. The lag for an uninsulated wood frame wall is about two hours, and for a fully insulated frame wall about five hours.

Temperature Gradients

These temperature variations, important though they are in determining the heat losses and gains, and thus affecting building operating costs, are equally important in that they largely determine the conditions of service imposed on the material. The maximum range in temperature from winter to summer may be seen from Figs. 1, 2 and 3

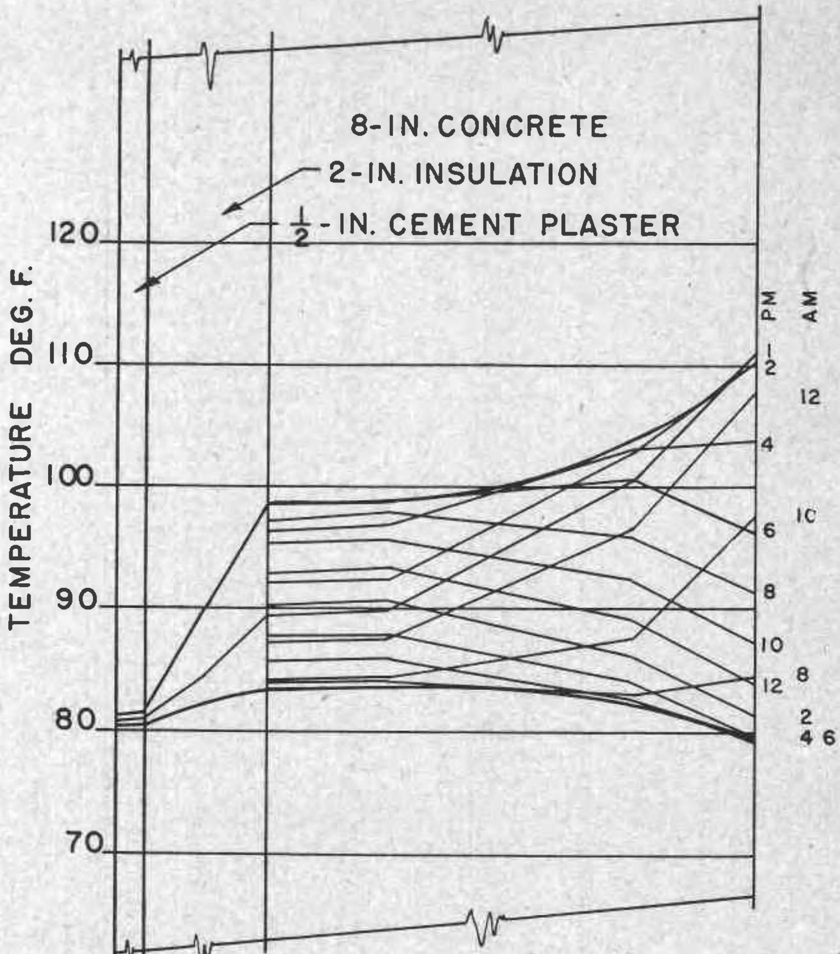

Fig. 6—Variation of temperature with time in an 8-in. concrete wall insulated on the inside, due to solar radiation in summer.

to be 133° for the plain concrete wall, 148° for the exposed surface of the wall insulated on the inside, and 160° for the ½-in. stucco finish over the insulation placed outside the concrete.

These temperature changes in concrete represent strains of from 1.1 to 1.35 inches per 100 ft. If fully restrained they would produce stresses of 2,330 to 2,800 lb. per sq. in. in concrete having a modulus of elasticity of 2.5×10^6 lb. per sq. in. The largest gradient in temperature for the winter condition in the concrete is shown to be 7° per inch throughout the plain wall of Fig. 1. This, if fully restrained, represents a stress of 980 lb. per sq. in., and under conditions of no restraint would cause a camber in the wall of 2.2 in. in 50 feet of height or of length.

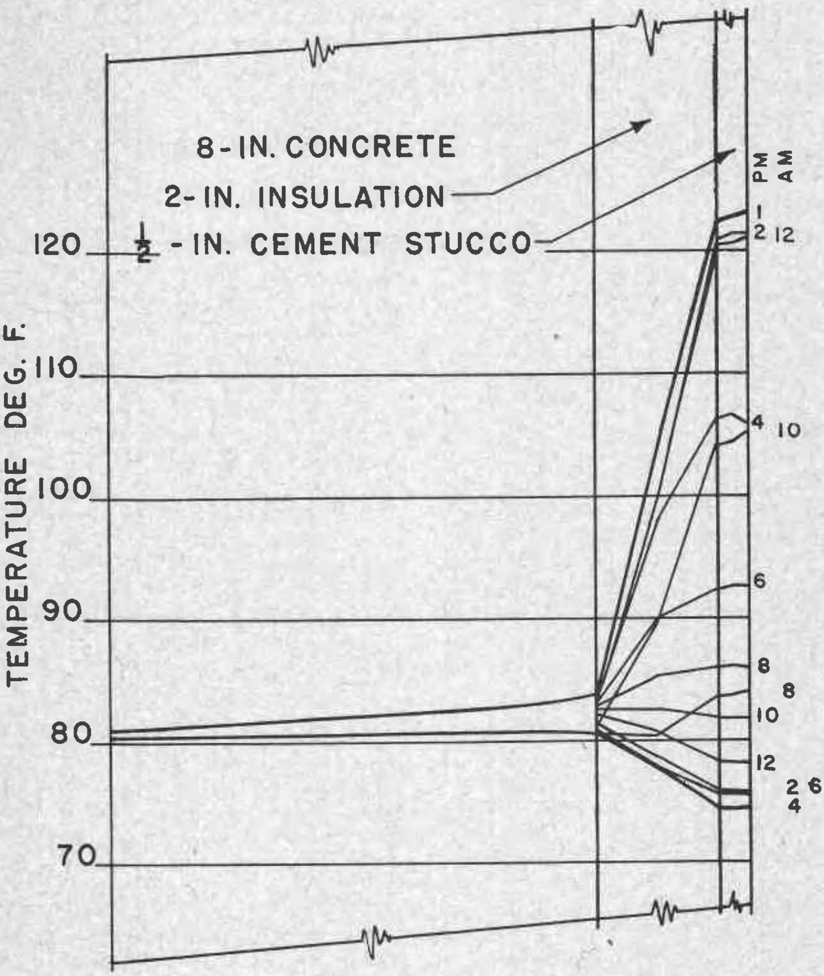

Fig. 7—Variation of temperature with time in an 8-in. concrete wall insulated on the outside, due to solar radiation in summer.

The maximum gradients in the concrete are considerably reduced, to about 1¼° per inch for the winter condition, for both insulated walls. The maximum summer gradients however are very severe, although confined to the outside of the concrete and restricted in duration, at 7° per inch for the uninsulated wall and 5° per in. for the wall insulated on the inside. When the insulation is placed on the outside, the gradients in the concrete are drastically reduced, being less than 1° per inch for the summer condition and, as previously noted, 1¼° per inch for the winter condition.

The implications of these results in relation to the service required of the material will be obvious. The farther out, thermally, the material is placed in a wall, the more severe is the temperature range which it will experience from winter to summer. Substantial thicknesses of high heat capacity materials experience sharp gradients when exposed to solar radiation.

For the three-component wall used as an example, a choice may be made as to whether the main structural element (in this case the concrete) or the insulation and outside covering are to be subjected to the most severe temperature variation. The concrete can be protected if placed inside the thermal barrier. Consideration must now be given to the effects of position on the service requirements in relation to other phenomena, principally moisture conditions.

Moisture in Materials

Control of water vapour and of liquid water were listed separately under major considerations, mainly to conform to the procedure which might be followed in design of dealing with them independently. For present purposes however, transformations of vapour to liquid to ice and back again occur so frequently within a wall, not only with position in the wall but with time, that they may be conveniently considered together as moisture.

Water in its various forms presents far more problems, not only in wall design but in building construction and operation, than any other factor or group of factors. It is involved first of all in most materials manufactured in situ, such as concrete, plaster and mortar. It is present everywhere, to some degree, and its presence is necessary for many of the deteriorating reactions which can take place in a wall, notably freeze-thaw breakdown, and corrosion.

It is responsible for the swelling and shrinkage of wood, as well as of other materials, and is frequently involved in the breakdown of finishes and coatings of various kinds, particularly those which are installed as protection against it. Despite the frequency of its occurrence and the difficulties for which it is responsible, it continues to be treated by the engineer largely as a "hydraulic" fluid moving under the influence of gravitational forces, and as a convenient fluid to use in the transport of heat and as an intermediary in the conversion of heat into work.

Applied scientists in soil science, especially in agriculture, have made the greatest advances toward an adequate understanding of the action of water in materials ([8]) ([9]). Much remains to be learned, and it will be necessary to go increasingly to the fields of chemistry and physics for assistance. Several books would be required to refer even briefly to all the scientific information pertinent to the role of water in building problems. Yet it is possible to sketch briefly the picture as it presently appears.

The engineer is not well prepared by his day-to-day experiences in dealing with water from the hydraulics point of view, for an understanding of the large forces brought into play when water becomes finely divided, as in the wetting of materials. Although familiar with the meniscus which forms at the water surface in a capillary tube, and the explanation for its occurrence, he is seldom led to consider the implications of this when the capillary system becomes very fine.

Table 1 shows the relationship between capillary bore, tendency to water rise or negative hydraulic head, pF, and relative humidity over the meniscus, in capillary tubes.

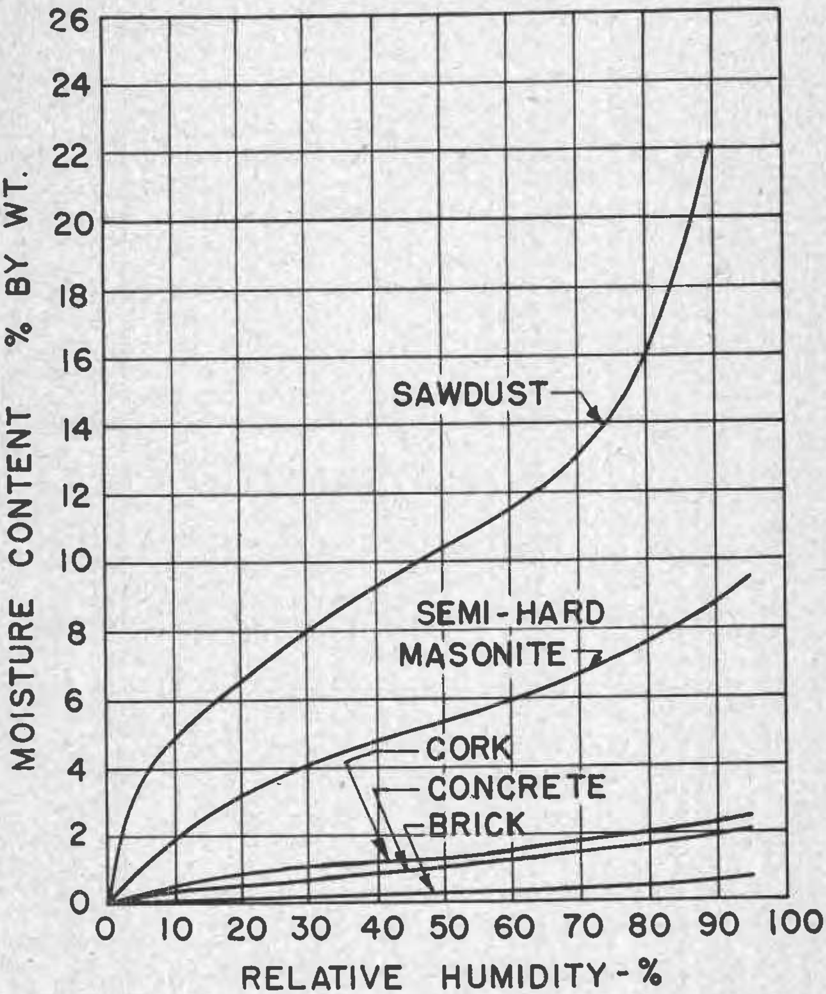

Fig. 8—Moisture taken up by various building materials at different relative humidities. (Data taken from Johansson (12)).

The basis for the calculation of these values may be found in texts on physical chemistry or on soils. The extraordinary range of values of the potential capillary rise makes it convenient to use a logarithmic scale. The one now frequently used in soils work is the pF scale introduced by Schofield which is given by the common logarithm of the potential water rise in centimetres ([10]).

As the capillary bore decreases, the curvature of the meniscus becomes sharper and the surface forces become larger, as is reflected in the higher potential capillary rise. Correspondingly, the vapour density, and therefore the vapour pressure at equilibrium over the curved surface, is decreased over that which would exist over a flat water surface at the same temperature. This can be expressed also in terms of relative humidity at equilibrium over the curved surface.

The water at the curved surface is sometimes said to be under tension, and the tendency to rise is referred to as capillary suction. These terms, although of value initially for comprehension of the phenomenon, are actually a hindrance to proper appreciation of the forces acting. Capillary potential is to be preferred, as a term, to capillary suction. It implies not only the tendency to capillary rise, but also the state of the water at the curved surface which is at a depressed free energy level by virtue of the forces acting on it.

Many of the common building materials: wood, brick, stone and concrete, have pore structures in the form of cells, tubes and spaces between particles as between packed spheres. While the shape, size arrangement, distribution, and degree of interconnection of these pore structures may vary widely from one material to the other, they are capable of acting like capillary tubes and of taking up water and holding it under conditions of *negative hydraulic head* ([3]) ([11]).

A necessary condition to capillary rise of water is that the material involved shall be one which is wet by water, indicating forces of attraction between the water boundary and the material surface. When the material is one which is not wet by water, the forces are repulsive, the curvature of the meniscus is reversed and, instead of capillary rise, capillary depression is produced.

Adsorption

Some further understanding may be achieved by considering the sorption of water molecules on the surfaces of certain materials. Strong forces of attraction are exerted by the surfaces of certain materials on

TABLE 1.—Capillary Potentials for Water in Ideal Capillary Tubes

pF	Capillary diameter inches	Equivalent Negative hydraulic head, ft.	Relative humidity, %
0	1.2×10^{-1}	3.28×10^{-2}	
1	1.2×10^{-2}	3.28×10^{-1}	
2	1.2×10^{-3}	3.28	99.99
3	1.2×10^{-4}	3.28×10	99.92
4	1.2×10^{-5}	3.28×10^{2}	99.27
5	1.2×10^{-6}	3.28×10^{3}	93.00
6	1.2×10^{-7}	3.28×10^{4}	48.43
7	1.2×10^{-8}	3.28×10^{5}	0.07

water molecules. Such materials will readily adsorb water molecules from the atmosphere. When the surface is completely covered by a single packed layer of molecules a second and a third and then many layers of molecules will form in succession, each layer less tightly held than the preceding one.

When the material is one which presents a large effective surface area, the amounts of water which may be taken up and held may be as much as 10 to 40 per cent of the dry weight of material. The molecules in the first layer being strongly attracted, are at a low free energy level, with each succeeding layer, less strongly held, at higher and higher free energy levels.

When the space over the material is saturated with water vapour, the adsorption process will continue until the final molecular layers are at the energy level of the water vapour in the space, that is, at the energy level of a flat water surface at the same temperature. When the space is only partially saturated with water vapour, which is then at a lower energy level, the sorption process will stop sooner, at a point where the energy level of the sorbed water is equal to that of the partially saturated vapour in the space.

By this time, however, all the very fine capillary structure may be filled with water molecules, while the larger pores may be only partially filled, with all water surfaces at curvatures representing equal free energy levels throughout. The equilibrium vapour pressure, or the corresponding relative humidity in the space over the water surface may be used as a measure of the free energy level. The free energy level can also be expressed in terms of the curvature of the surface in a capillary tube, or of the height to which water would be lifted in a capillary tube, for the same free energy level.

Water can be adsorbed on a surface-active material under forces different than those in a capillary tube. Its free energy level can still be expressed in terms of the rise in an equivalent capillary tube, if desired. As the amount of adsorbed water is increased, capillaries begin to be filled and movement of liquid through them becomes possible under differences in free energy level. There is still no agreement as to the possibility of movement of the adsorbed layer, before any capillaries are filled, without an intermediate change to the vapour state. As the pores become filled flow under positive hydraulic head becomes possible.

The great virtue in these concepts lies in the fact that they make possible the adoption of a single continuous scale for potential, over the whole range from negative to positive hydraulic heads, from adsorbed films through to complete saturation. This, in turn, makes possible a rational approach to a study and understanding of the problems of when, where and at what rate water will move, whether it be present in the vapour or the liquid state, or both.

The equilibrium moisture contents taken up by various materials when in equilibrium with water vapour in the air at various relative humidities, are shown in Fig. 8. As may be noted by reference to Table 1, a 95 per cent level of relative humidity corresponds to a pF of 4.6, a capillary diameter of 3×10^{-5} in. or a negative hydraulic head of 1,300 feet. The weight of water taken up by the various materials of Fig. 8 at 95 per cent humidity reflects directly the volume of the pore space which has been filled by water at a free energy level equivalent to that in a capillary of 3×10^{-5} in. diameter.

As the humidity is raised above 95 per cent, larger and larger capillaries become filled and increasing amounts of water are taken on. By the time the humidity reaches 100 per cent, the negative hydraulic head will be zero. Observe that the relative humidity varies substantially only over a portion of the range of negative hydraulic heads of interest, at the "dry" end of the scale, furthest from saturation. Techniques have been developed for measurement of these potentials over practically the whole range ([11]), and much data relating potentials to moisture contents is available for soils. Little application of these techniques has as yet been made to other materials.

Moisture Migration

It follows from the above discussion that moisture will tend to migrate in a material until the potential is equalized throughout.

Further, if two materials containing moisture are placed in contact, the moisture will be redistributed between them until the potentials are equal. If no continuous capillary paths are provided so that movement of liquid through the capillaries is not possible, vapour transfer may take place, until the conditions for equilibrium at equality of potential are established.

When data on potentials at various moisture contents are obtained for building materials it will be possible to predict quantitatively many such equilibrium conditions. It has already been found for example, that in a particular brick-mortar combination, equilibrium was established at a 1 per cent level of moisture content by weight in the brick with 10 per cent moisture content in the mortar[1].

[1]Observations made by the Division of Building Research, National Research Council.

When coefficients of permeability are known, as well as the potentials, we may predict not only the direction of moisture migration, but also its rate. Again, considerable data is available in the soil science field, but relatively little for other materials, over the range where the capillaries are partially filled and liquid movement can occur. Much work has been done, however, on vapour flow through building materials.

Permeabilities for vapour flow have been measured, and Babbitt ([13]) and others ([22]) have shown how such data may be used to predict condensation in walls, and to determine approximately the vapour barrier required. This work has to be greatly extended to cover a wider range of materials, and to include moisture movement in the range of higher humidities. Logical extension of this work to higher humidities brings in consideration of liquid movement through capillaries as well as vapour movement.

Potentials arising in other ways than those discussed also have to be considered. Chemical potentials existing between solutions of different salt concentrations separated by a membrane cause a flow of water through the membrane to the solution of higher concentration. This will be recognized as osmosis. When water is forced through a porous medium, an electrical potential known as a streaming potential can be developed.

It is well known that when electrical potentials are applied under certain conditions, water can be caused to move. This action is now referred to as electro-osmosis. Winterkorn ([14]) has suggested a close analogy between electro-osmosis, and the movement of liquid water under a temperature gradient which he calls thermo-osmosis. Several investigators have shown that moisture does migrate under a thermal gradient, in the direction of lower temperature ([15]) ([16]), but there is not yet agreement on whether it migrates as liquid to the cold side, as proposed by Winterkorn for soils, or only as vapour.

There is evidence that substantial vapour movement may take place in sawdust under a temperature gradient and that this is accompanied by a return flow under capillary potential and by a substantial movement of heat as latent heat in the vapour ([17]). There is also evidence that appreciable vapour movement can take place in soil in the direction of decreasing temperature, with return capillary flow in the reverse direction ([18]).

Some work has been done on the change in dimension of materials with change in moisture content. This has been confined largely to wood and wood products, which take on substantial amounts of water vapour from the air, and which experience appreciable dimensional changes as a result ([19]). Some data are also available on brick and on concrete ([20]). Much more data are required.

Efflorescence

Two interesting cases of moisture migration may now be discussed. Both involve efflorescence, the appearance of salts on a masonry surface. Efflorescence can be a serious problem when it spoils the outside appearance of walls, or results in disruption of coatings. It occurs as a result of the transport of dissolved salts by liquid water movement to a surface at which evaporation can take place, leaving the salt incrustation on the surface. As such, it is therefore a ready-made indicator of water migration. It can be eliminated either by controlling the water, or by avoiding if possible the soluble salt in the masonry. There is some indication that salts not present in the original masonry may be formed when certain materials are brought together.

Several experimental masonry huts under observation at Ottawa during the winter of 1951-52 showed marked efflorescence effects, with the disappearance and reappearance of the surface salt deposit at frequent intervals[2]. The disappearance of salt always coincided with wetting by rain, confined almost entirely to the east side of the huts. The reappearance of the efflorescence coincided largely with improvement in the general drying conditions provided by the outside air, following wetting and frequently followed a moderate reduction in temperature.

Except under heavy rains, all water falling on the outside of the wall was absorbed. It seems likely that the same salt was involved in successive reappearances. The reappearance of salt following a reduction in temperature could be evidence of liquid movement to the outside, brought about by a temperature gradient, as proposed by Winterkorn. Yet evaporation must have occurred to cause the salt to appear.

It is likely that lowered night temperatures reduced the dewpoint sufficiently to create drying conditions during the day, and that the process was one of evaporation of water at the surface, reducing the moisture content and thus the capillary potential there, and bringing about an outward liquid migration. Two things seem certain: the salt can only be carried by liquid, and is only caused to appear as an incrustation by evaporation of the water from the solution.

Efflorescence may be commonly observed in the Ottawa district, and probably elsewhere, on brick mason-

[2]Observations by the Division of Building Research, National Research Council

ry walls in areas immediately under pre-cast concrete window sills. It seems the concrete and brick in combination may provide more soluble salts than are present in masonry alone. The localization of the effect may, however, come about because frequent wetting is also confined to the area under sills.

Projecting sills and ledges hold substantial amounts of snow. The window and the sill are frequently more highly conducting thermally than the rest of the wall. The outside surface temperatures may therefore be high enough to produce melting of the snow. Solar heat gain, however, is a much more probable cause of melting where there is exposure to the sun. The sol-air temperature is shown in Fig. 4 for 52° N. latitude for a surface of medium color and for an arbitrarily selected but representative winter temperature variation. A sol-air temperature of 35° is attained although the air temperature averages only 7° F. throughout the day.

Analysis of the periodic heat flow shows that under these conditions a plain concrete wall will attain a surface temperature of 33½°, sufficient to cause melting of the snow. The water so formed probably penetrates the sill, and enters the brickwork on its way to the surface, carrying salts which are deposited on evaporation.

It will be apparent that the approach to moisture migration which has been developed and so far largely applied only in soil science, can be extended to a study of a wide range of moisture problems in buildings, with great profit. There are many implications for new attacks on the problems of waterproofing, efflorescence, paint peeling, spalling and other forms of deterioration brought about by freezing, as well as many other problems in which water is involved. Experiments must be carefully planned to take into account the possibility of any or all of the phenomena described. This applies equally to experiments on heat flow when water is present.

Moisture in Walls

There are several possible phases of the problem of moisture in actual walls. First, water may be present as a result of in-situ manufacturing and wet weather during construction. This frequently leads to moisture problems during the first year or two of operation of a new building. Evidence seems to establish definitely that a wet wall can be expected to transmit water more readily than a dry one. Once the high level of construction moisture has been reduced, a more or less normal condition for a particular building can be expected. Wall moisture can then originate within the building, usually by transmission of water vapour into the wall followed by condensation, or from outside the building from rain or melting snow.

The use of a vapour barrier to control vapour flow into a wall is now well established for wood frame walls. The same reasoning and the same techniques are presently applied, largely by analogy with wood frame walls, to insulated masonry constructions. It is not yet conclusively shown that this is entirely satisfactory.

The problem is complicated in masonry walls by several factors. The total water passing through a proper vapour barrier in one winter represents an increase of moisture content of about 0.25 per cent in an outer 4-in. brick withe, while several times this amount of moisture may readily be added in a single rain. When a vapour barrier is used, the wall can lose moisture only to the outside. In summer, hot sun following a rain drives moisture as vapour to the inside of the wall, and condensation behind the vapour barrier can occur.

Consideration of these and other problems has led several people to question the soundness of certain features of present practice in masonry wall construction. Difficulties are frequently encountered whenever the wall construction is such as to provide unbroken capillary paths from the exposed weather surface to the inside of a wall. The cavity wall with properly designed metal ties is one answer to this.

Cavity walls incidentally were intended to cope with moisture problems and not to provide improved thermal properties, as is commonly supposed in Canada. The cavity wall as usually designed has several undesirable features. Cavities are created by separating the main structural membrane into two or more membranes, tied together to act as the main structural unit. Temperature variations will usually be exaggerated, leading to increased differential thermal expansions between the separate withes.

The outer withe, usually of a capillary material, is also subjected to exaggerated changes in moisture content relative to the others. If the material exhibits moisture expansion, further differential movements may result. Hot sun on a wetted outer withe can still drive water as vapour back into the inner withes, producing wetting by condensation there. For this reason it has been recommended that cavities should be ventilated to outside, by air passages through the outer withe. If placed at different elevations, these would promote air circulation to carry off vapour to the outside, under wet-hot summer conditions of the outer withe.

Such ventilation would also be compatible with the winter requirements for elimination of vapour entering from inside, by venting to the outside. The winter thermal performance of the wall would also be affected, perhaps quite seriously, and special consideration of thermal properties would become necessary. The summer problem of heat gain might under certain conditions be improved by ventilation of the cavity to outside.

The use of waterproof membranes over or in masonry construction, in the outer portion of a wall, while effective in preventing liquid movement from outside, may also dam up water by condensation behind such membranes in winter, and lead to other difficulties, perhaps even spalling.

Fundamental principles for moisture control may now be set out:—

1. Vapour flow from inside the wall in winter must be restricted by vapour barriers or otherwise, at a plane sufficiently warm to prevent condensation on the warm side of such barrier.
2. Walls must be capable of limiting the entry of water from outside into capillary material in the main part of the wall, while permitting the flow of water vapour to the outside under winter conditions.

In addition, it would appear to be desirable to require a minimum of potential water storage capacity on the outside of the wall, or if such potential capacity exists, to separate it capillary-wise from the inner portions of the wall, and to minimize by venting the transfer of vapour to the inside under summer conditions.

Johansson [21], in Sweden, has this to say, in translation,—

> "However, it is clearly unwise to allow walls, whether of brick or porous cement, to be exposed to heavy rain. They absorb water like a blotting paper, and it would therefore be a great step forward if an outer, water-repelling screen could be fitted to brick walls, with satisfactory characteristics from the point of view of appearance, mechanical strength and cost.
>
> "This screen could be applied so that water vapour coming from within is automatically removed by ventilation of the space between wall and screen.
>
> "If a rain screen of this type is used, the thermal resistance of the wall can be considerably increased for only a slight increase of expense, by employing one of the highly porous, thermally isolating materials now obtainable. With a highly porous layer between the actual wall and the rain screen, the house would retain its good characteristics as regards heat capacity, sound isolation and fire risk. At the same time it would be guaranteed free from moisture, even in the worst weather, and moreover be extraordinarily well isolated thermally."

The approach to wall design as presented by Johansson, is perhaps an idealized one, to be modified to conform to many practical considerations. It is perhaps not the only idealized approach possible, but so far as can be predicted, it can be made to satisfy simultaneously all the various requirements, and it is possible of achievement. It permits a wider selection of materials, since the number of properties which any particular material or element must provide can be reduced.

Consider a wall which consists basically of a structural masonry panel. It is to be used as the inner part of the wall. Plaster finish may be applied directly to it on the inside. Selected largely for its strength properties, it will therefore tend to be high in thermal conductivity, and to experience only a small drop in temperature across it under heat flow conditions.

The vapour barrier can therefore safely be placed outside it, since the wall is to be insulated. The temperatures at the outside of the main panel will be sufficiently high to eliminate the possibilities of condensation of vapour from inside in winter. Further, the vapour barrier can now be of the film type, applied directly to the outer surface of the panel, on a large, accessible flat surface, uninterrupted by structural members.

Insulation and an outside covering have still to be added, and must be fastened to the structural panel while still maintaining the efficacy of the vapour barrier. These can now be very light, the insulation can be of rigid form, and the outer weather screen can be light in weight. It can be of sufficient strength only to maintain itself against weather forces. The weather screen can, if necessary, have low moisture storage properties, thus reducing the tendency to vapour flow into the wall in summer.

The main structural material is now maintained at conditions deviating little from those indoors, which will usually be determined by considerations of comfort of occupants and therefore regulated within narrow limits. It is relieved of all but small temperature and moisture variations and gradients, and will not be subject to freezing action.

A much wider range of materials can now be considered since the durability requirements are greatly relieved. The main panel, being highly conducting, will maintain by conductivity in the plane of the wall, very uniform inside surface temperature conditions, without the usual cold spots caused by high-conductivity ties, beams, bolts, etc. Further, the effects on surface temperature of any ties or fastenings passing through the main insulation will also be greatly reduced. This is of particular importance in buildings constructed for high indoor humidities.

Detailing around openings is not necessarily complicated and can be greatly simplified. Window design can now be approached in a more fundamental fashion by substituting transparent sections in both the main panel and the weather screen. The use of heavy, thermally conducting sills and other high heat paths presently associated with windows can if desired, be largely avoided.

One warning must be given. The main panel must be sufficiently highly conducting in relation to the main insulation, so that the vapour barrier on the outer or cold side remains properly located, thermally, in the wall. Further, the creation of air spaces on the warm side, by additional sheathing, will result in objectionable temperature reductions at the vapour barrier, as well as substantial variations in room-side surface temperatures caused by convection in the air space.

Even these difficulties can be avoided if heat is added to the main panel, or into the bottom of the warm-side air space if one is used. A further extension of this could result in the production of a wall in which room-side surface temperatures are kept equal to room temperature throughout, with no thermal exchange between the wall surface and the room.

Conclusion

The fundamental requirements of walls in general have been discussed. While there are many possible considerations, these can be reduced to nine major ones. These must not be dealt with independently, since they are highly inter-related. Features introduced in a design on a limited basis to overcome one difficulty may create other more serious problems.

The role played by water in association with building materials has been emphasized. Much useful direction can be obtained from the information and techniques already developed in soil science. There is great need for a proper appreciation of the capillary movement of water, and for a comprehensive treatment of it which properly relates vapour movement, combined vapour and capillary movement, and saturated flow. Experimental studies in this field must take proper account of the various ways in which potentials to produce migration of water may arise.

The importance of temperature and moisture conditions together in determining the durability required of materials to be used in various ways and at various locations in a wall has been stressed. The conditions under which a particular material will be required to perform can be greatly influenced by the properties of the individual components selected, and by the ways in which they may be associated in the wall.

The proposed wall design, in principle, satisfies the major requirements by the use of several components, avoiding as far as possible the use of more than one component to satisfy a single requirement. The structural strength and rigidity are provided in one main structural panel with the vapour barrier, insulation and outside weather screen provided in separate components. Each is relieved, so far as possible, of the functional requirements of the others. The approach recommended is realistic in that it accepts limitations in the properties provided in the available materials, and attempts to use them so as to achieve the best results.

There is another idealized approach, quite widely supported, which assumes that a single material can be found which will permit the construction of a simple, low cost, monolithic wall satisfying all the requirements. This approach is not realistic, since this material ideally ought to exhibit no thermal expansion, no moisture expansion, be impermeable to moisture, provide resistance to heat flow as well as strength in reasonable thicknesses, and be otherwise stable and durable.

The greatest obstacle to the acceptance of the wall construction recommended for consideration will be in the changed exterior appearances which will result if the proposals outlined are carried to their logical technical conclusion. However, Nature's laws are immutable whereas many ideas on aesthetics are not. In the meantime, there are many engineering-type structures in which these principles may be followed without difficulty so long as the inside weather is reasonably within the range of human comfort. There are many types of buildings in which moderately high humidities must be carried where, so far as can presently be seen, serious moisture problems can only be avoided readily in this way. When, however, special conditions are to be met which depart markedly from those assumed here, such as might be the case in a cold storage building, an entirely different solution may be indicated.

It is proposed that the overall requirements can best be met in this manner. This is in contrast to another idealized approach, quite widely held, which envisages the development of a monolithic wall of a single material, which will satisfy simultaneously all the requirements.

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