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EFFECT OF MOISTURE ON THE FIRE ENDURANCE OF BUILDING ELEMENTS

BY

T. Z. HARMATHY

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EFFET DE L'HUMIDITE SUR LA RESISTANCE AU FEU DES ELEMENTS DE CONSTRUCTION

SOMMAIRE

L'effet de l'humidité sur la résistance au feu des éléments de construction est étroitement lié à la teneur en humidité et, par conséquent, aux caractéristiques de sorption des matériaux. Une teneur en humidité élevée peut causer l'effritement. L'auteur décrit le mécanisme probable de l'effritement causé par l'engorgement de l'humidité et il propose un critère ayant pour but de déterminer à quel point de saturation fractionnaire des pores on peut s'attendre à l'effritement (Eq. (8)). S'il ne se produit pas d'effritement, la présence de l'humidité favorise la résistance au feu. Une équation empirique établit un rapport entre le pourcentage de gain de résistance au feu dû à une humidité de 1% et la résistance au feu lorsqu'il n'y a pas d'humidité (Eq. (20)). L'auteur présente un nomogramme ayant pour but de faciliter l'évaluation de l'effet de l'humidité sur la résistance thermique au feu (Fig. 9). L'auteur évoque l'utilisation possible de ces résultats dans le domaine des essais de résistance au feu.

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ANALYZED

EFFECT OF MOISTURE ON THE FIRE ENDURANCE OF BUILDING ELEMENTS[1]

By T. Z. Harmathy[2]

Synopsis

The effect of moisture on the performance of building elements in fire is closely related to the amount of moisture, and in turn, to the sorption characteristics of materials.

High moisture content may result in spalling. The probable mechanism of moisture clog spalling is discussed, and a criterion is developed for the fractional pore saturation at which spalling can be expected (Eq 8).

If spalling does not occur, the presence of moisture is beneficial for the fire endurance. An empirical equation has been found which correlates the percentage gain in fire endurance due to 1 per cent moisture with the fire endurance in the dry condition (Eq 20). A nomogram is presented to facilitate estimation of the effect of moisture on thermal fire endurance (Fig. 9).

Possible utilization of the results in the field of fire endurance testing is discussed.

The realization that the moisture inevitably present in almost any building material may have a marked effect on the performance of building elements in fire, and may present a serious problem in the reproducibility of the results of standard fire tests, prompted a significant revision of ASTM Method E 119[3] in 1959. So significant was this revision that, if enforced retrospectively, it would have invalidated hundreds of fire test results.

Although this revision helped in calling attention to the fact that such problems exist, the solution offered by it cannot be regarded as more than temporary. If the effect of a variable on the result of some test is clearly proved, but not known quantitatively, the correct attitude is to face the problem by studying the relation between the cause and effect. One may seemingly dispose of that variable by prescribing it a constant value during the test, but further unexpected problems may arise while the basic problem remains unanswered.

Some problems coming in the wake of setting an upper limit to the equilibrium relative humidity[4] of fire test specimens are already seen clearly, others have so far remained unnoticed. Frequent questions include: Should the upper limit be 75, 70, or 50 per cent? Can forced drying be permitted and under what conditions? Will a specimen that satisfies such mois-

[1] Although this paper deals with brick and concrete walls only, most of the conclusions are applicable to other types of building materials.

[2] Research officer, Fire Research Section, Division of Building Research, National Research Council, Ottawa, Canada.

[3] Methods of Fire Tests of Building Construction and Materials (E 119), *1964 Book of ASTM Standards*, Part 14.

[4] Equilibrium relative humidity is an abbreviated term meaning equilibrium pressure of water vapor in the pores of solid, expressed as relative humidity.

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ture requirements also satisfy the more basic requirement that a specimen must be representative of what the actual construction is in service?

It is impossible to find valid answers for all circumstances. Some materials can be tested at high equilibrium relative humidities without any noticeable effect from the presence of moisture. Others will yield markedly different performances even at 5 per cent change in the equilibrium relative humidity. Some materials can be forced-dried at very high temperatures, others change significantly in their characteristic features if subjected to drying at an early stage. For some building elements, those to be erected in dry areas or where the heating season is long, the representative moisture content may be much less than that in equilibrium with 50 per cent relative humidity (RH). In some other

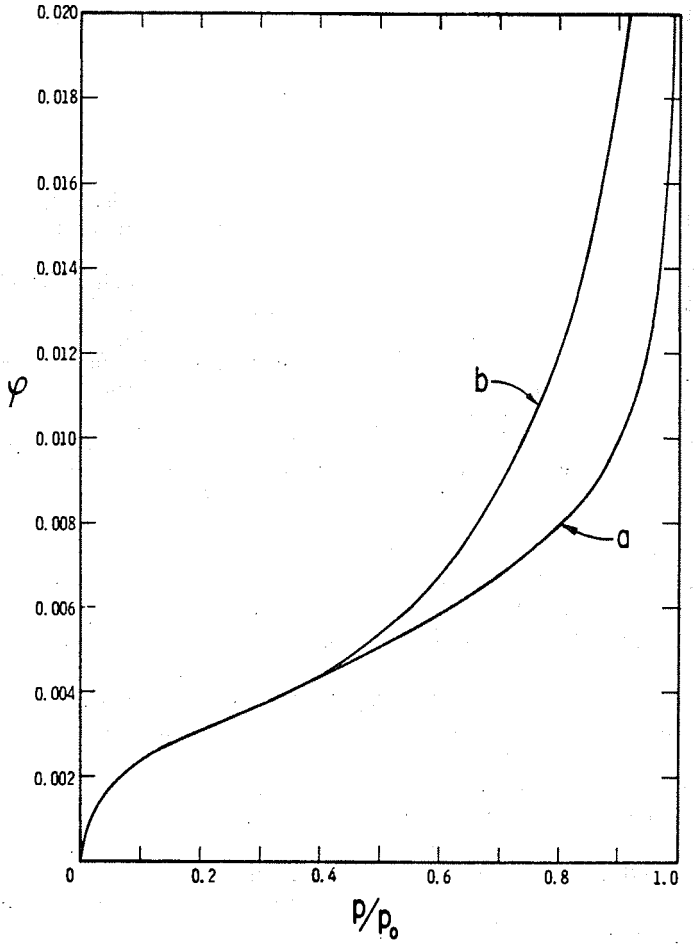

FIG. 1—Calculated Sorption Isotherms of a Certain Clay Brick.
(*a*) Adsorption Branch
(*b*) Desorption Branch

cases, because of specific service conditions, an average equilibrium RH higher than 75 per cent may be anticipated.

It is obvious that none of these problems would arise if the effect of moisture on the fire endurance were known. Test specimens could be subjected to fire tests at any (or almost any) moisture content; thus, the time devoted to conditioning could serve a very useful purpose—that of attaining the physical properties characteristic of the material under actual service conditions.

This paper presents the results of investigations into the effect of moisture on the fire endurance of building elements. The possible utilization of the results in the field of fire endurance testing will be discussed in the last section.

SORPTION CHARACTERISTICS OF BUILDING MATERIALS

The effect of moisture on the fire endurance of building elements is, of course, closely related to the amount of moisture, and, in turn, to the sorption characteristics of materials. The basic laws governing the adsorption of moisture, or *adsorbate*, in general, by a porous solid (*adsorbent*) are discussed by Sereda and Hutcheon.[5] They note that the amount of moisture held by a solid at various vapor pressures, in other words, the shape of sorption isotherms, depends on the specific surface, the effective porosity, and the pore geometry (basic pore shape, pore size distribution, etc.) of the solid, and that in the domain of capillary condensation marked sorption hysteresis can be experienced.

Although these sorption characteristics can be determined from relatively simple experiments (1),[6] it is often desirable to have an estimate of them. Harmathy, in another paper (2), shows how the basic laws of adsorption and some experimental data can be used to estimate the moisture sorption isotherms and isosteres of building materials.

Figure 1 shows the moisture sorption isotherms of a certain type of clay brick, obtained by calculations. The shape of the curves can be regarded as typical of building materials in general, with the important exception of concrete. In the case of concrete, the hysteresis loop extends to the whole $0 < p < p_0$ pressure range.[7] To understand the cause of this unusual behavior one should realize that the binding energy for some water molecules held in the portland cement paste by chemical bonds is less than the energy needed to dislodge the most firmly held adsorbed molecules during drying. Consequently, at some advanced stage of drying, desorption and partial dehydration will take place simultaneously. Since the amount of water held by adsorption cannot be determined exactly, that part of water which is dislodged by some standard drying procedure is more accurately called evaporable water, rather than moisture. For similar reasons, the amount of water retained by the hydrated cement throughout the drying should be termed nonevaporable water.

Obviously, in the case of concrete, the reference state of the material is not its "dry" state, but a state determined by some standard drying procedure. Among the various drying techniques two are generally accepted as standard: (1) drying over ice at −78.5 C (sublimation temperature of CO_2), so-called *D* drying, and (2) drying in an oven at 105 C.

In the light of this discussion it seems most probable that the unusual shape of sorption isotherms of concrete is due to partial or complete rehydration, during adsorption, of the water of constitution

[5] See p. 3.

[6] The boldface numbers in parentheses refer to the list of references appended to this paper.

[7] Symbols are listed at the end of the paper.

lost at very low pressures during desorption.

The sorption characteristics of portland cement paste and concrete depend very strongly on the degree of hydration (1,3,4), and thus on the age, conditioning procedure, and some other factors. Under ordinary circumstances a sufficiently large mass of concrete can retain enough water in its pores to secure the progress of hydration for a very long period after the removal of forms and protecting covers. If, however, the concrete is

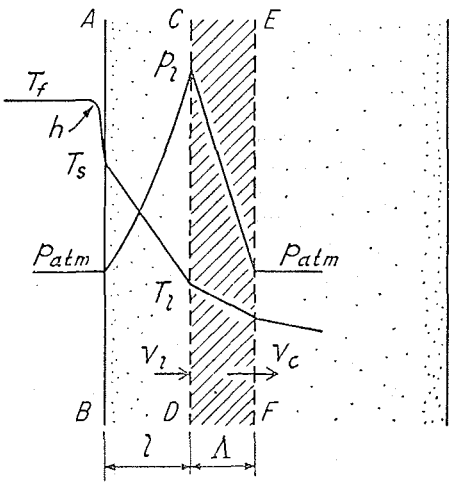

FIG. 2—Diagram of Moisture Clog Formation.

subjected to forced drying, the hydration slows down considerably as the RH in the pores becomes lower than 95 per cent, and stops completely at 80 per cent (5).

SPALLING

Because of the marked differences in the sorption characteristics of various building materials the amount of moisture that these materials hold at normal atmospheric conditions may be very significant in certain cases, or barely noticeable in others.

As already mentioned, the presence of moisture is sometimes detrimental, sometimes beneficial. As for its detrimental effect, there is now sufficient evidence that excessive moisture is at least one of those factors which may cause violent spalling of concrete at some early stage of fire exposure.

The factors affecting the most common mode of spalling, the so-called thermal spalling, have been under scrutiny for several decades. It is generally accepted that increasing values of the group $\sigma_f(1 - \nu)/E\alpha$ indicate, at least approximately, an increasing resistance to thermal spalling. The $(1 - \nu)/E\alpha$ group always appears in expressions obtained for thermal stresses in solids, if the calculations are based on the assumptions that E, ν, and α are constant in the temperature range concerned, and the material is perfectly elastic. Such assumptions are obviously not applicable to concrete, which exhibits a mixed elastic-plastic behavior at any load even at room temperature and, owing to decomposition, often marked shrinkage instead of expansion upon heating. Because of these characteristics, concrete is rarely liable to thermal spalling.

A probable mechanism of spalling of concrete, called moisture clog spalling,[8] during fire exposure was described by Shorter and Harmathy (6) as follows. When heat begins to penetrate into a concrete slab, desorption of moisture starts in a thin layer adjoining the surface exposed to fire. A major portion of the released vapors leave toward the colder regions and become readsorbed in the pores of some neighboring layer. As

[8] The difference between thermal spalling and moisture clog spalling occurring during standard fire endurance tests is easily recognizable. Moisture clog spalling is generally more violent and the thickness of the dislodged layers is greater, about 1 in. Spalling of concrete may also be due to other factors, such as excessive deformation, expansion of reinforcing steel, or crystalline transformation in certain aggregates, especially those of high quartz content.

the thickness of the dry layer gradually increases, a completely saturated layer of considerable thickness (called a moisture clog here), builds up at some distance from the exposed surface. A little later, a sharply defined front forms between the dry and saturated layers (Fig. 2). Further desorption will obviously take place from this frontal area (indicated by Line *CD*).

In the meantime the temperature of the exposed surface keeps rising, and a very steep temperature gradient develops across the dry layer resulting in high heat flow and intensified desorption at the *CD* plane. Having little passage toward the colder regions, the vapors have to leave through the dry layer, gradually expanding and meeting increasing resistance along the flow path. With further steepening of the temperature gradient there will be a rapid pressure buildup at Plane *CD*.

If the resistance of the pores to moisture flow is not too high, under the effect of the developed large pressure difference, the moisture clog (Region *CDEF*) begins to move toward the colder regions and the pressure buildup soon levels off. If, on the other hand, the permeability of the material is low, the pressure at Plane *CD* continues to grow and will eventually exceed the ultimate tensile strength of the material. When this condition is reached, a layer of a thickness approximately equal to that of the dry layer separates from the material.

If this suggested mechanism is correct, one could expect that material properties, such as porosity, permeability, ultimate strength, and thermal conductivity (by affecting the heat flow through the dry layer) will appear in an expression, the value of which determines whether moisture clog spalling will take place at a given moisture content. Because of the very involved mechanism of combined heat and moisture flow, it is unavoidable to base the derivation of such a criterion on a greatly simplified mathematical model, as follows.

Figure 2 is a schematic illustration of the conditions arising in a concrete slab exposed to fire at a stage when the formation of the dry layer and moisture clog is completed, and the desorption takes place from Frontal Plane *CD*. If it is assumed that a fraction δ of the moisture previously desorbed from Layer *ABCD* has been readsorbed by Layer *CDEF*. The following relationship is obtained between Λ and l

$$\Lambda = \delta l \frac{\varphi}{\epsilon - \varphi} \quad \text{(1)}$$

Assuming, furthermore, quasi-steady-state conditions within Region *ABCD*,[9] and applying heat balance to Surface *AB*, the surface temperature can be expressed as

$$T_s = \frac{T_l + (hl/k)T_f}{1 + (hl/k)} \quad \text{(2)}$$

and the heat flow as

$$q = \frac{h(T_f - T_l)}{1 + (hl/k)} \quad \text{(3)}$$

The rate at which Front *CD* recedes due to vaporization is[10]

$$v_l = \frac{q}{Q\rho_w\epsilon} \quad \text{(4)}$$

The velocity of the moisture clog, Region *CDEF*, as a whole, can be expressed from Darcy's law

$$v_c = \frac{\kappa}{\eta} \frac{p_l - p_{atm}}{\Lambda} \quad \text{(5)}$$

[9] This is a reasonable assumption. Observations and calculations indicate that within the period when spalling might occur (10 to 25 min in the case of standard fire tests), the variation rate of the average temperature of the Region *ABCD* is not very significant.

[10] Effective porosity is the volume fraction permeable to the adsorbate (water) and is generally slightly less than the true porosity.

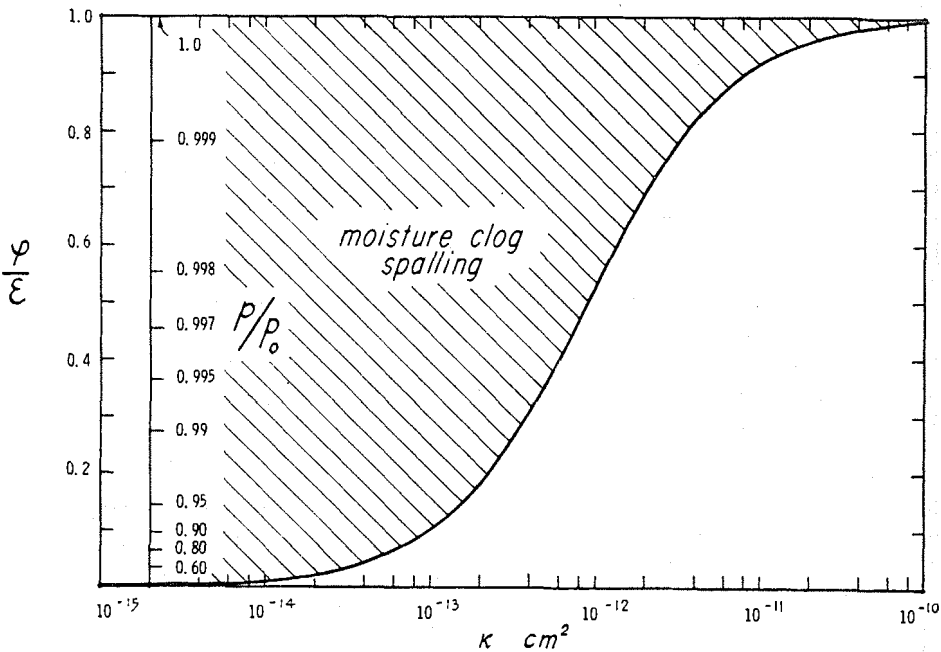

FIG. 3—Moisture Clog Spalling Liability Curve. Assumed Properties: $\epsilon = 0.30$, $\sigma_f = 17.0 \times 10^6$ dyne/cm², $k = 1.0 \times 10^{-2}$ J/cm sec deg K.

The condition $v_c > v_l$ can be interpreted that the moisture clog moves fast enough to prevent further pressure buildup at Plane *CD*. On the other hand, $v_c < v_l$ means that the moisture clog cannot yield to the pressure, and the pressure buildup continues owing to increasing rate of vaporization of Front *CD*. Thus, spalling will take place if

$$p_l - p_{\text{atm}} = \sigma_f \quad \text{(6)}$$

and

$$v_c < v_l \quad \text{(7)}$$

By combining Eqs 1 and 3 to 6, with Inequality 7, the following criterion is obtained for the fractional pore saturation, φ/ϵ, at which disruption of the concrete slab is expected

$$\frac{\varphi}{\epsilon} > \frac{1}{1 + (A/\epsilon\kappa\sigma_f)[k/(k + B)]} \quad \text{(8)}$$

where

$$A \equiv \frac{\delta l \eta h (T_f - T_s)}{Q \rho_w} \quad \text{(9)}$$

and

$$B \equiv hl \quad \text{(10)}$$

and both are considered approximately constant. After assigning plausible values to δ, l, η, etc. in Eqs 9 and 10

$$A = 2.1 \times 10^{-5} \text{ dyne}$$

$$B = 3.6 \times 10^{-2} \text{ J/cm sec deg K}$$

or, if one prefers substituting κ in darcies, σ_f in psi, and k in Btu/ft hr deg F

$$A = 0.031 \text{ darcies in.}^2\text{/lb}$$

$$B = 2.1 \text{ Btu/ft hr deg F}$$

Figure 3 shows the variation of allowable fractional pore saturation with permeability, calculated by using Eq 8 with $\epsilon = 0.30$, $\sigma_f = 17 \times 10^6$ dyne/cm² (250 psi) and $k = 10^{-2}$ J/cm sec deg K

TABLE 1—MATERIALS AND GEOMETRIES STUDIED FOR DETERMINING THE EXPLICIT FORM OF EQ 12.

No.	Material	Composition, % by weight	Nature of Study	Properties of Material Plotted in	Moisture Content, per cent by volume	Geometries[a]
1	Concrete 1 (assumed)	15.6 hpc[b] 84.4 quartz gravel	computer calculations	Fig. 4*a*	0 4.0 8.0	S-3⅝, S-5⅝, S-7⅞, H-7¾–83.3, H-7¾–77.8, H-7¾–71.4, H-7¾–55.6
2	Concrete 2 (assumed)	15.4 hpc 84.6 anorthosite rock	computer calculations	Fig. 4*b*	0 4.0 8.0	S-3⅝, S-5⅝, S-7⅞, H-7¾–83.3, H-7¾–77.8, H-7¾–71.4, H-7¾–55.6
3	Concrete 3 (assumed)	25.3 hpc 74.7 expanded shale	computer calculations	Fig. 5*a*	0 4.0 8.0	S-3⅝, S-5⅝, S-7⅞, H-7¾–77.8, H-7¾–71.4, H-7¾–55.6
4	Concrete 4 (assumed)	19.6 hpc 80.4 expanded shale	computer calculations	Fig. 5*b*	0 4.0 8.0	S-3⅝, S-5⅝, S-7⅞, H-7¾–77.8, H-7¾–71.4, H-7¾–55.6
5	Concrete 5 (existing)	17.5 hpc 82.5 expanded shale	fire endurance tests	Fig. 6*b*	0 to 20.8	S-3⅝, H-5⅝–89.1, H-5⅝–68.8
6	Brown clay brick (existing)	...	computer calculations and fire endurance tests	Fig. 6*a*	0 to 21.8	S-2½, S-4, S-6, S-8[c]
7	Insulating fire brick (existing)	...	fire endurance tests	Fig. 6*b*	0 to 9.9	H-8¼-46.7

[a] S-3⅝ means solid wall of 3⅝ in. thickness.
H-7¾–83.3 means hollow wall of 7¾ in. over-all thickness and 83.3 per cent solid.
[b] Hydrated portland cement.
[c] Computer calculations only.

(0.578 Btu/ft hr deg F). If one knows the sorption isotherms of the concrete, the scale on the vertical axis can be changed to read RH instead of fractional pore saturation. In Fig. 3 the desorption branch of the isotherm shown in Fig. 1 was used to illustrate how the transformation of scale is done. (Obviously, the adsorption branch should be used when equilibrium conditions are attained by wetting instead of drying.)

According to Fig. 3, moisture clog spalling is not likely to happen even at complete pore saturation if the permeability of the material is higher than about 5×10^{-11} cm^2 (0.005 darcies). Although this value seems to be within the expected range, it should be remembered that at present no experimental proofs are yet available for the confirmation of the validity of Eq 8.

In the case of bricks, the permeability is rarely lower than 0.005 darcies, thus moisture clog spalling is very unlikely. A recent series of experiments seemed to support this conclusion. It was also found, however, that brick constructions are often liable to thermal spalling.

It may be noticed that the permeability of mature portland cement pastes is several orders of magnitude lower than that of fresh pastes (3,7); thus, with aging concretes become more vulnerable to moisture clog spalling.

GAIN IN THERMAL FIRE ENDURANCE

If spalling is not expected to take place, the presence of moisture in building materials is beneficial for fire endurance. The primary reason is obvious: The absorption of heat associated with the desorption of moisture checks the rise of temperature in a building element during fire exposure, delaying the development of various undesirable phenomena which eventually lead to the failure of the building element.

Since, directly or indirectly, it is always the rise of temperature that causes the failure of a construction, the thermal performance of a building element, expressed in a conveniently defined unit (in terms of thermal fire endurance)[11] is generally a reliable measure of its overall performance in fire. Thus a figure of merit, expressing the beneficial effect of moisture on the performance of a construction, can be defined by

$$\psi = \frac{\tau_\varphi - \tau_d}{\tau_d \varphi} \quad \text{(11)}$$

This figure of merit of moisture expresses the percentage increase in thermal fire endurance in relation to the percentage (by volume) moisture content. Previous theoretical studies (8) indicated that for a given material and geometry of construction $(\tau_\varphi - \tau_d)/\tau_d$ is approximately proportional to φ, thus, in general

$$\psi = f \text{ (properties of materials, geometry)} \quad \text{(12)}$$

but is independent of φ.

To determine the explicit form of Eq 12, 90 computer calculations and 49 fire endurance tests have been performed. The materials and geometries studied are summarized in Table 1.

Concretes 1 to 4 are assumed materials. Each was selected to represent an extreme case in the group of either dense or lightweight concretes. Since quartz is the best and anorthosite probably the poorest thermal conductor among natural rocks used as aggregates, the thermal fire endurance yielded by Concrete 1 can be regarded as the lowest, and that yielded by Concrete 2 as the highest obtainable at a given geometry with dense concretes. Similarly, the properties of Concretes 3 and 4 were selected in such a way that no lightweight (nonautoclaved) concrete is expected to

[11] The thermal fire endurance is the time at which the average temperature on one side of a construction exceeds its initial value by 139 C, when the other side is exposed to a standard fire specified by ASTM Method E 119.

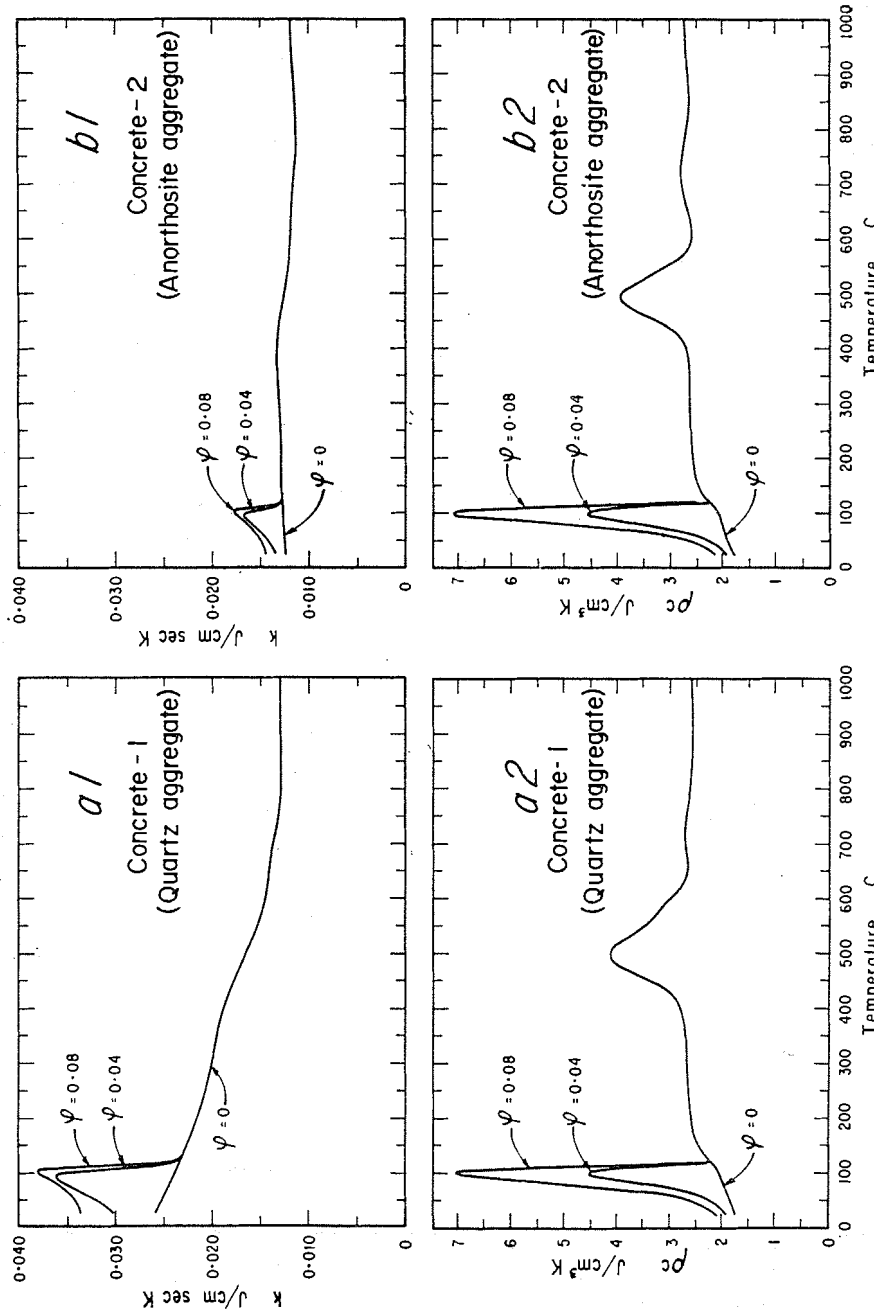

FIG. 4—Thermal Properties of Two Dense Concretes.

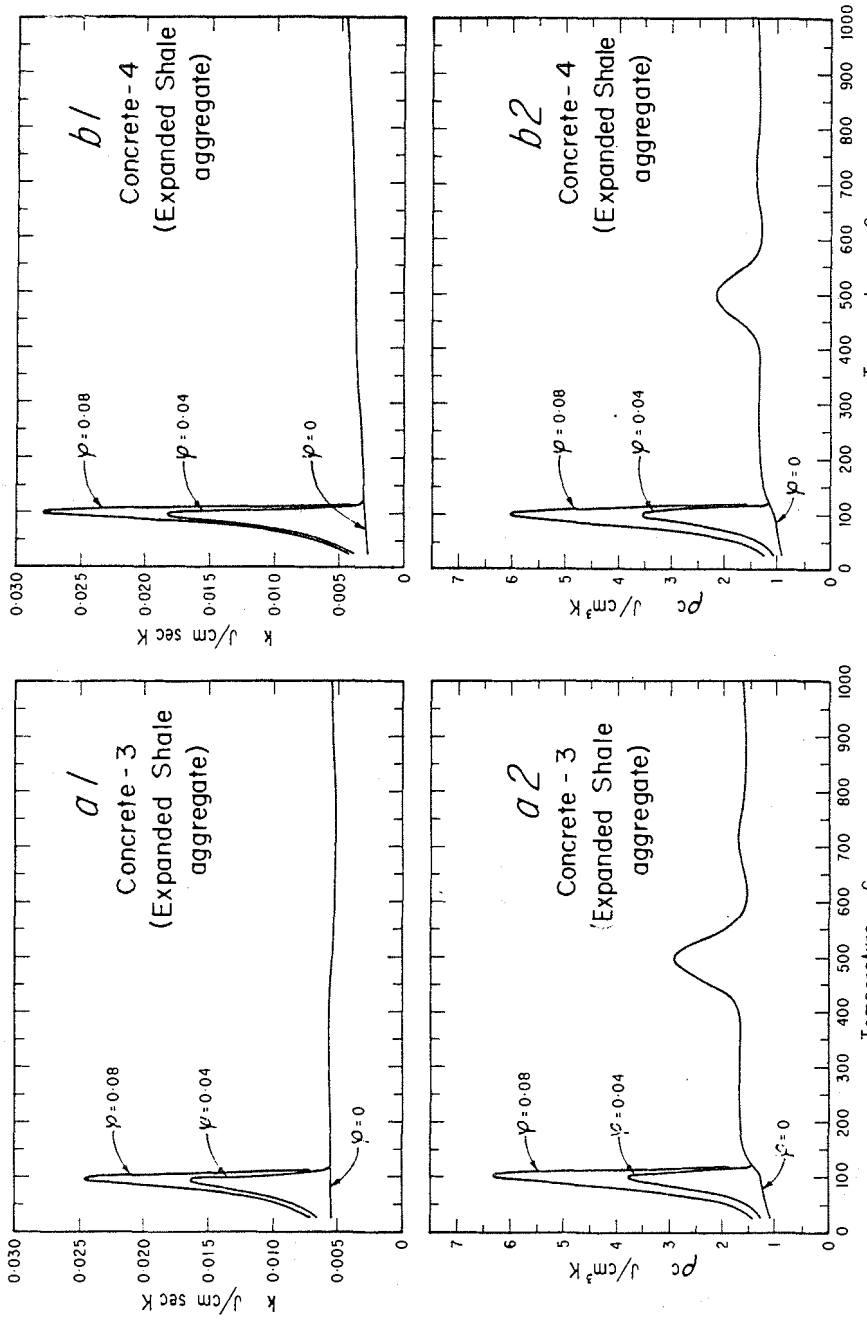

FIG. 5—Thermal Properties of Two Lightweight Concretes.

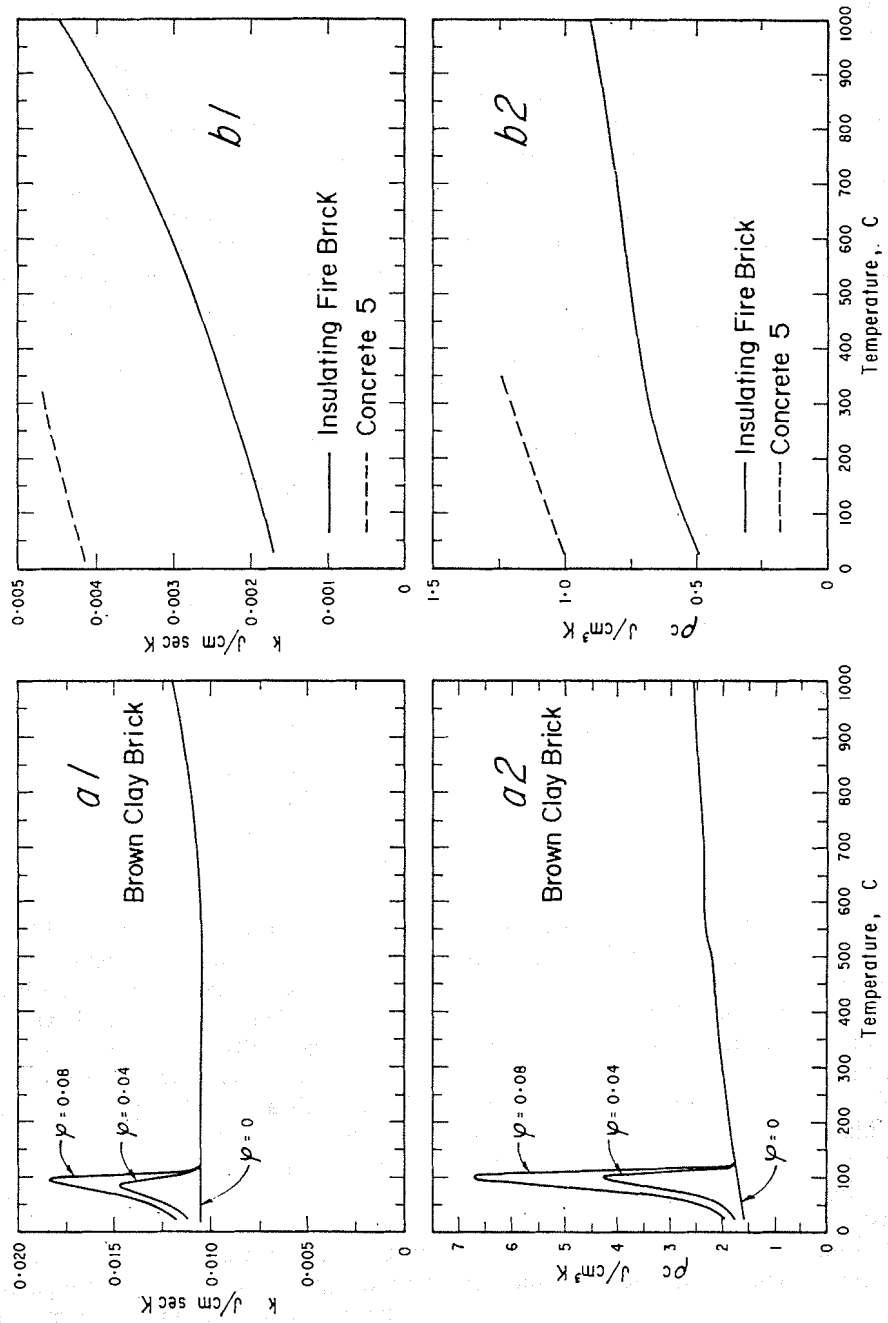

FIG. 6—Thermal Properties of Three Existing Materials.

yield lower thermal fire endurance than Concrete 3, or higher fire endurance than Concrete 4. The thermal conductivity versus temperature, and heat capacity versus temperature[12] curves for these materials (Figs. 4 and 5) are naturally theoretical curves, yet based on numerous experimental results and thermodynamic data concerning the constituent materials. The methods of calculation will be reported elsewhere.

The k versus temperature and ρc versus temperature cruves for Concrete 5, Brown Clay Brick, and Insulating Fire Brick, are entirely or principally experimental curves, determined by means of a variable-state method (9).

In all figures the curve sections representing 4 and 8 per cent (by volume) moisture content have been obtained by calculations. The effect of moisture on the thermal conductivity has been evaluated by using a somewhat modified form of Krischer's theory (10).

It should be emphasized that fire endurance calculations based on such k versus T, and ρc versus T curves corrected for the presence of moisture, could lead to strictly correct results only in the case of such fictitious solids which have zero permeability in the direction of heat flow and infinite permeability perpendicular to the heat flow. In such hypothetical solids neither moisture (adsorbate) nor vapor could migrate along or opposite to the direction of heat flow, and the desorbed vapors could leave the solid infinitely fast along isothermal surfaces. Real solids, of course, have finite permeability in all directions, and since under conditions arising during fire exposure, the paths representing the least resistance to fluid flow and the heat flow lines are generally coincident, one can expect marked moisture and vapor migration both along and opposite to the heat flow. As mentioned earlier, the following types of mass migration are conceivable: (1) migration of desorbed vapor in the direction opposite to the heat flow, primarily under the effect of pressure gradient, (2) apparent moisture (adsorbate) migration in the direction of heat flow by desorption-resorption sequence, induced by gradients of pressure and of vapor concentration, (3) moisture

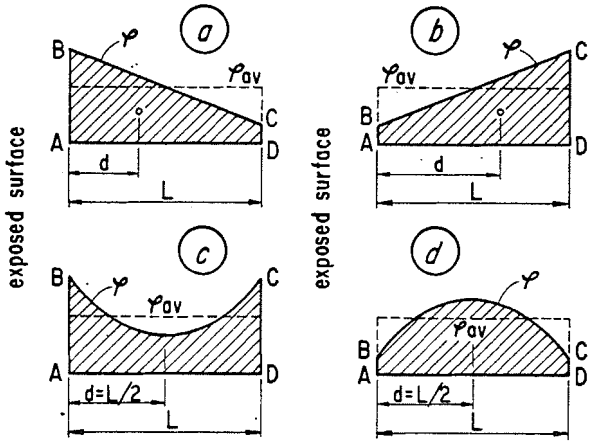

FIG. 7—Elucidation of Rule of Moisture Moment.

[12] Note that in these graphs ρc should be interpreted as total heat capacity, obtained as the tangent to the volumetric enthalpy versus temperature curve (8).

(adsorbate) migration in the direction of heat flow under the effect of pressure gradient.

To learn about the probable effect of these migrations on heat transfer, a series of numerical analyses was undertaken to determine the thermal fire endurance of four $3\frac{3}{4}$-in. brick walls, all containing 5.3 per cent (by volume) moisture, but distributed over the thickness in different ways. The results indicated that the moisture distribution had a very significant effect on the thermal fire endurance. It was found that the increase in fire endurance was proportional, not to the moisture content, but to its moment about the surface exposed to fire.

This finding, which may be called the rule of moisture moment, is an extremely useful tool of theoretical fire endurance rating. Its application to practical problems is illustrated in Fig. 7 where four different moisture distributions across a wall of thickness L are shown. In all four cases, the average moisture content is the same, in other words, Areas $ABCD$ are identical. As stated by the rule of moisture moment, the gain in fire endurance is proportional to the product of Area $ABCD$ and the distance of the center of gravity of this area from the exposed surface d. It is now easy to see that the fire endurance corresponding to a distribution shown in Fig. 7*a* will be less than that corresponding to a distribution shown in Fig. 7*b*. On the other hand, if the moisture distribution is symmetrical about the center line, as in the cases shown in Figs. 7*c* and 7*d*, the distance of the center of gravity of Areas $ABCD$ from the exposed surface is always equal to the half thickness of the wall; thus, if Areas $ABCD$ are equal, equal fire endurances will result.

With the conventional conditioning procedures the symmetry of moisture distribution in wall fire test specimens is always ensured, thus, the result of the fire test is expected to depend on the average moisture content only, and to be independent of the moisture distribution.

It is now possible to evaluate the effect of the three types of mass flow on the thermal fire endurance. In the case of Type 1 flow the desorbed vapors proceed toward hotter layers, absorb sensible heat, and hinder the flow of heat through the construction. With Type 2 migration the heat flow toward the surface opposite to the fire exposure is aided by a very significant latent heat transfer, but with the displacement of moisture the moisture moment gradually increases. Finally, with Type 3 migration a slight increase of heat flow caused by transfer of sensible heat by the moving moisture will be strongly overshadowed by the increase of moisture moment. It is seen now that migration Types 1 and 3 will definitely, and Type 2 will possibly, result in an increase of thermal fire endurance over the value calculable by the assumption of no mass migration along and opposite to the heat flow. It seems most probable, therefore, that the ease of mass transfer in these directions, and in turn the permeability of the material, is the most important factor affecting the gain in thermal fire endurance.

As Sereda and Hutcheon noted, knowledge in this field has not yet developed far enough to enable one to deal with the problem of combined heat and mass transfer in its real complexity. From calculations based on the assumption of no mass transfer perpendicular to the isothermal surfaces one can only expect to find the lower limit of the fire endurance of moisture containing building elements. It will be shown, however, that if combined with experimental results, even this information can be of considerable value.

Although learning about the thermal properties of materials in the tempera-

ture interval of interest generally represents the bulk of the work, there are other problems to solve before successfully calculating the thermal fire endurance. First, a rigorous definition of the standard fire exposure should be found which could supplement the vague definition in ASTM Method E 119.

After evaluating a large number of temperature measurements taken from the surface exposed to fire of standard fire test specimens, it was concluded that conditions met during a fire endurance test are well approximated by taking the standard fire exposure equivalent to the transfer of radiant heat to the fire-exposed side of a construction from a black surface, the temperature of which varies according to the so-called time-temperature curve of ASTM Method E 119. Nevertheless, to facilitate computer calculations, the time-temperature curve was replaced by the following analytic expression

$$T_f = 294.4 + 750[1 - \exp(-0.06326t^{1/2})] + 2.840t^{1/2} \quad (13)$$

This is only slightly different from the so-called *CSTB* function (11), and approximates the time-temperature curve within ±6 C in the 15-min to 8-hr interval.

The laws governing the mechanism of heat flow through a building element during fire exposure are fairly well established. In the case of solid (not hollow) walls the heat flow is one dimensional, and hardly any problem arises. As mentioned, at the side exposed to fire, the heat transfer can be regarded as taking place by radiation between a black body of temperature T_f, (representing the furnace in standard fire tests) and the surface of the building element at $x = 0$, through a nonabsorbing medium. The heat flux can be calculated from the Stefan-Boltzmann law, and by combining it with the Fourier law the following boundary condition results

$$k\frac{\partial T}{\partial x} + \sigma e\,(T_f^4 - T^4) = 0 \qquad \text{at } x = 0 \quad (14)$$

Within the solid, the heat transfer takes place by conduction according to the Fourier equation

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) = \rho c\frac{\partial T}{\partial t}, \qquad \text{for } 0 < x < L \quad (15)$$

At the surface opposite to fire exposure, the heat transfer is by combined convection-radiation mechanism to nonreflecting surroundings. The radiant heat transfer is again calculable from the Stefan-Boltzmann law. The convective transfer can be described satisfactorily by an empirical equation given by McAdams (12). A combination of these laws with the Fourier law yields the boundary condition for the unexposed surface

$$k\frac{\partial T}{\partial x} + \sigma e(T^4 - T_o^4) + \beta(T - T_o)^{5/4} = 0, \qquad \text{at } x = L \quad (16)$$

The initial condition is

$$T = T_o, \quad \text{for } 0 \le x \le L, \quad \text{when } t = 0 \quad (17)$$

In all calculations T_o was taken as 294.4 K (21.2 C), and e was selected as 0.9—a good average for the materials listed in Table 1. The fact that e decreases slightly with an increase in temperature was disregarded.[13]

In the case of hollow walls, the heat flow is, at least approximately, two-dimensional. Besides the increased labor in solving such cases, a new problem arises —the extremely complicated mechanism of heat transfer within an enclosure bounded by gray surfaces.[14] In the

[13] Owing to the very high temperatures the decrease of e may be significant at the exposed surface. This fact, however, has little effect on the result because the heat transfer coefficient is very high anyway, and the heat flux is controlled by the thermal resistance of the solid (13).

[14] See (12) for the definition of gray surfaces.

present series of studies Gebhart's method (10) of calculating the radiation-exchange in enclosures was utilized. The heat transferred by convection between the surface elements of the enclosure was also taken into account.

All calculations were executed on IBM 1620 and 7090 computers. The computer programs were based on a numerical procedure similar to that described by the author (8). The correctness of the assumed mechanisms of heat flow, presented by Eqs 13 to 17, was proved by the case of the $2\frac{1}{2}$- and 6-in. brick walls (in oven-dry condition), where the difference between the computed and experimental results was less than 5 min.

After expressing the results of computer calculations in terms of figure of merit of moisture, it was found that ψ could be correlated with τ_d with fair degree of success. (This finding is, of course, not at variance with Eq 12, since τ_d is function of the properties of materials and geometry of construction.) The ψ versus τ_d plot, based on computed results, is shown in Fig. 8. Although the plot was based on information obtained for five materials of widely different characteristics and several different geometries, all points seem to lie within a relatively narrow band. The best curve representing the mean can be given approximately by

$$\psi = \frac{4.3}{1 + 0.25\tau_d} \quad \text{.....(18)}$$

This equation is expected to yield the lowest possible value of ψ at a given τ_d, and is strictly correct only for certain hypothetical materials.

As mentioned, to find the relation between ψ and τ_d, 49 fire endurance tests were carried out in the second part of

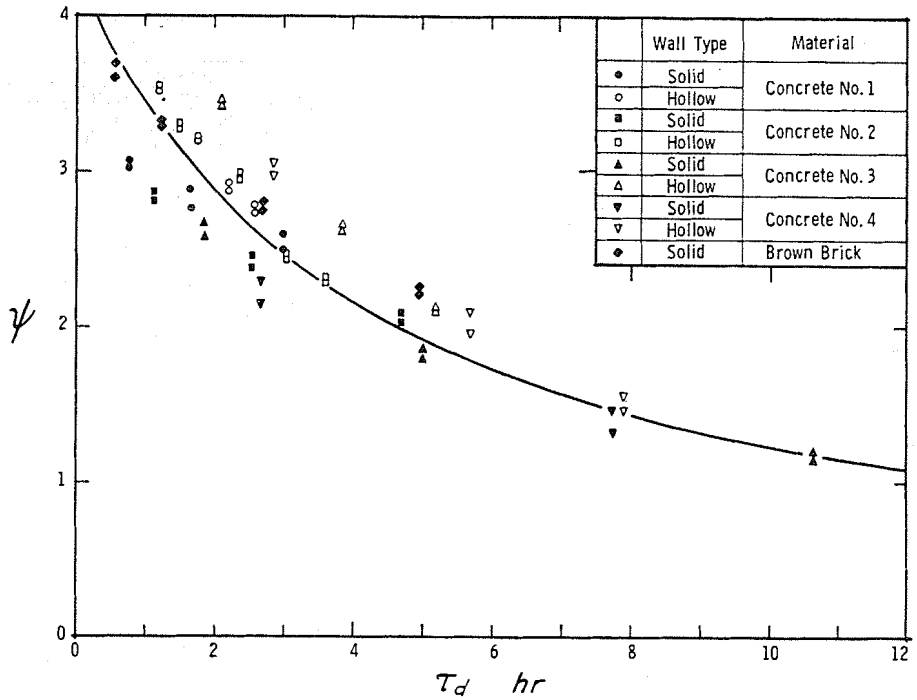

FIG. 8—Result of Computer Calculations.

the present series of investigations. All tests were performed on 32- by 32-in. specimens, using an electric furnace with 30- by 30-in. opening. The heat input was controlled to make the furnace temperature follow the standard time-temperature curve. The temperature of the unexposed surface was measured by three thermocouples placed under asbestos pads along a diagonal. Although these tests could not qualify in every respect for standard fire endurance tests. experience over several years has shown that there is no significant difference in thermal fire endurance values obtained by these small-scale tests and by full-scale standard tests.

Altogether, 17 specimens were built which represented three different materials and seven different geometries (Table 1). Four to five weeks after their construction all specimens were installed in a furnace and dried for 6 hr at about 105 C. The oven-dry weight of the specimens was recorded immediately after their removal from the furnace. Some were tested in oven-dry condition, others were transferred into polyethylene enclosures for storage and conditioning. Before the scheduled fire test, steam was introduced into the enclosure for a period necessary for the specimen to reach the desired moisture level. The actual moisture content was determined by weighing the specimen about 1 hr before the fire test.[15]

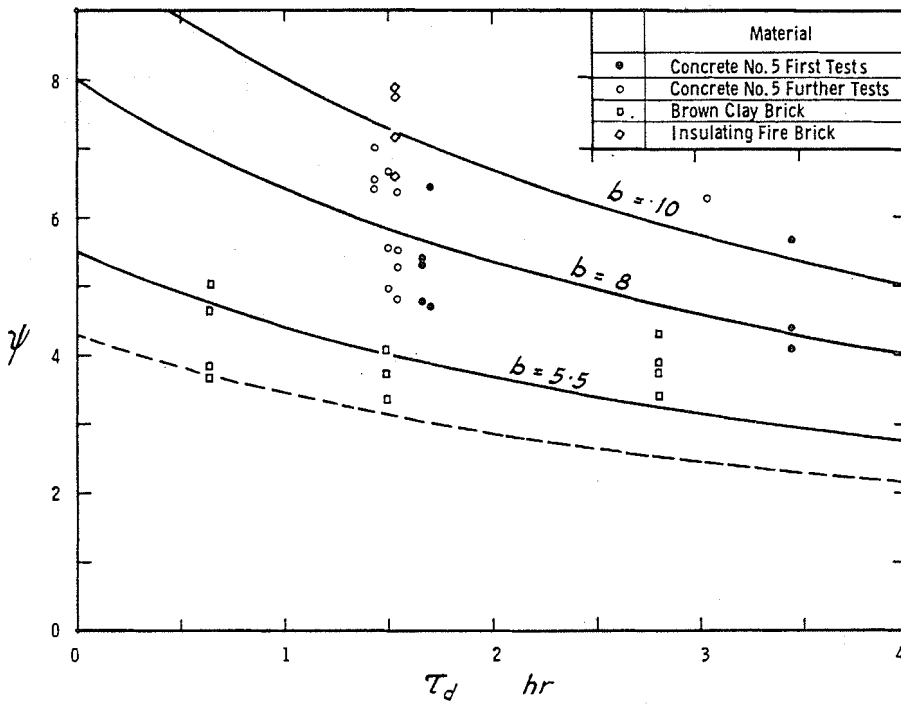

FIG. 9—Result of Fire Endurance Tests.

To obtain a sufficiently large number

[15] The moisture distribution in the specimens was unquestionably symmetrical; therefore, as noted in connection with Fig. 7, the distribution of moisture across the specimen was expected to have no effect on the fire endurance test results.

of experimental data, twelve of the specimens were subjected to fire test more than once. With specimens made from Concrete 5, some loss of the nonevaporable water content was experienced following the first test. No further dehydration could be detected during subsequent tests. Because the first test had undoubtedly brought about some permanent changes in the properties of concrete, once-tested concrete specimens were treated as if made from different material. The oven-dry weight of repeatedly tested specimens was taken as the weight immediately after the previous test.

The ψ versus τ_d plot based on this experimental series is given in Fig. 9. The considerable spread of the points may be understood in the light of the following observations: (1) The reproducibility of thermal fire endurance value was ± 5 min, (2) The estimated accuracy of the weight measurements was ± 100 g, equivalent to a moisture content of ± 0.1 to ± 0.3 per cent by volume, (3) Undoubtedly, there were more than negligible differences in the properties of specimens of supposedly identical materials.

In spite of the considerable spread of points, the following seem to have been proved. In practical cases ψ is always greater than the value calculable with the assumption of zero permeability in the direction of heat flow. (The ψ versus τ_d relation corresponding to this assumption is a dotted curve in Fig. 9.) As expected, ψ increases with the permeability of the material. The experimental results seem to support the assumption that the two most important variables on which ψ depends are τ_d and κ, that is

$$\psi \approx f(\tau_d, \kappa) \qquad (19)$$

Also, ψ decreases slightly with an increase in τ_d.

The spread of the points in Fig. 9 is somewhat overemphasized by the selection of the vertical scale. The total range of variation of ψ is, in fact, not too great (from 3.3 to 7.9); thus, further experiments aimed to find an explicit form of Eq 19 would serve little practical purpose. The accuracy yielded by Eq 20 will probably prove sufficient from the engineering point of view

$$\psi = \frac{b}{1 + 0.25\tau_d} \qquad (20)$$

where b is a function of κ and can be taken as:

$b = 5.5$ for brick, dense concretes, and gun-applied concretes,

$b = 8.0$ for lightweight concretes, and

$b = 10.0$ for cellular concretes.

The curves representing Eq 20 with these recommended values of b are also in Fig. 9.

DISCUSSION

The problems connected with an effort to standardize the moisture condition of fire test specimens have been discussed briefly. There are great differences in the sorption characteristics of building materials. At normal atmospheric conditions many building materials cannot hold sufficient moisture to affect the result of fire test to any appreciable degree; therefore, rigid insistence on a single standard conditioning procedure for all materials is inappropriate. On the other hand, for most concretes, the presence of moisture is only one problem, and an all-out effort to reduce the moisture content to some standard level may not give the results desired.

There is much information available (**4,15**) which shows that at 28 days, even under very favorable conditions, the hydration of the portland cement paste is far from being completed. It is obvious that not only the mechanical, but also

the thermal properties of concrete, are strongly dependent on the degree of hydration. Thus, terminating the hydration by subjecting the test specimen to accelerated drying at an age of 28 days, or even earlier, may result in a material which can hardly be regarded as representative of what it would become under normal service conditions.

If the effect of moisture on the fire endurance of a construction is known, the whole problem of conditioning may be considered in a completely different light. The process of conditioning need no longer be regarded as equivalent to drying. On the contrary, this process can serve its true purpose: the development of the microstructure which is characteristic of the material after several years' service.

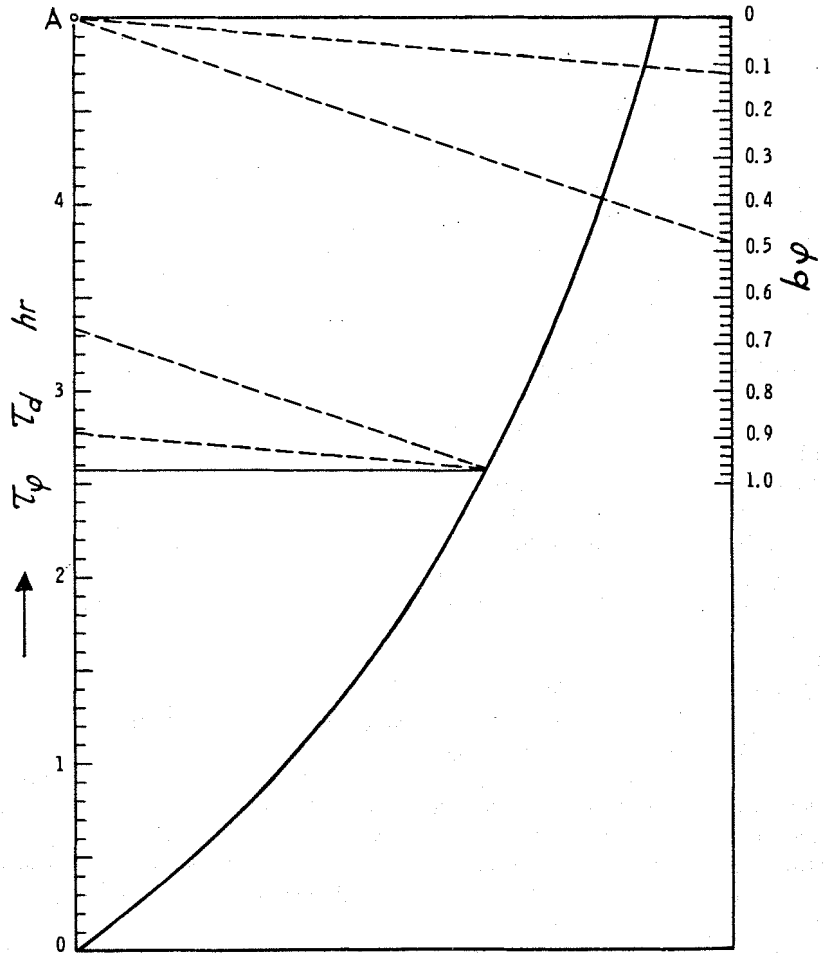

FIG. 10—Nomogram for Determining Moisture Effect on Thermal Fire Endurance.

Storage at moderately elevated temperatures (say 40 to 50 C) in an atmosphere of higher than 95 per cent RH for at least one month could probably be regarded as a desirable conditioning procedure for most concretes. It is known

that up to about 100 C the products of hydration reactions are practically unaffected by the temperature (16,17), but the rate of the reactions is greatly increased at elevated temperatures (4). If the material is not expected to spall, after a month of curing, the specimen can be subjected to fire test at relatively high pore saturation. If the material is liable to spall, forced-drying at about 90 C may be applied for a short period to reduce the moisture to a level probably to be met under adverse service conditions.

Of course, the reduction of a fire test result to some other moisture level is possible only if the moisture content of the specimen had been accurately determined prior to the test. The average moisture content of a specimen may be measured fairly accurately by means of a recently described sampling technique (18), if a sufficient number of samples are taken from well selected locations. Further increase in the accuracy is possible by a combination of sampling and weighing the whole specimen with the aid of load cells.

The correction of a fire test result for a different moisture content has three steps: (1) calculation of τ_d from experimental values of τ_φ and φ as described below, (2) application of the experimental or calculated sorption isotherm to find the value of φ under the expected service conditions, (3) calculation of τ_φ corresponding to this latter value of φ.

Step 1 involves the solution of Eq 21, which is a result of combining Eqs 11 and 20, for τ_d

$$\tau_d^2 + \tau_d(4 + 4b\varphi - \tau_\varphi) - 4\tau_\varphi = 0 \quad (21)$$

where, as mentioned earlier:

b = 5.5 for brick, dense concrete, and gun-applied concrete,
b = 8.0 for lightweight concrete, and
b = 10.0 for cellular concrete.

Although the solution of Eq 21 presents no problem, to facilitate the calculations a nomogram is given in Fig. 10. The same nomogram can be used to find τ_φ corresponding to a new φ value which is required in Step 3.

The use of the nomogram is illustrated by this example: A lightweight, concrete-block wall has yielded 3.33-hr fire endurance when tested at 6 per cent (by volume) moisture. Question: What is the fire endurance of the wall at 1.5 per cent moisture?

For lightweight concretes $b = 8.0$, thus $b\varphi = 0.48$ for $\varphi = 0.06$. Connect the point corresponding to this value on the right-hand side scale with Point A. A line drawn parallel to this from 3.33 on the left scale will cut the curve at 2.58 hr which is the value of τ_d. For $\varphi = 0.015$, $b\varphi = 0.12$. Again, connect this point on the right scale with Point A, and a line drawn parallel to this from the previously determined point of the curve will intersect the left scale at the value of τ_φ pertaining to 1.5 per cent moisture, 2.77 hr, in this case.

It would seem a good practice to regard, not the experimental fire endurance, but the value corresponding to the dry condition, τ_d, as the basic information. This could then be used to assign specific values to the fire endurance in specific applications. According to this concept, the wall mentioned in this example may get 3-hr fire endurance when used as an outside wall in certain regions where the average RH is high, but may be regarded only as a 2-hr wall when used as a partition in another region where the winter heating season is long.

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lished with the approval of the Director of the Division.

SYMBOLS

A = constant, defined by Eq 9, dyne
b = factor, function of κ, hr
B = constant, defined by Eq 10, J/cm sec deg K
c = specific heat, J/g deg K
d = distance, explained in Fig. 7, cm
e = emissivity, dimensionless
E = modulus of elasticity, dyne/cm^2
f = function
h = heat transfer coefficient, J/cm^2 sec deg K
k = thermal conductivity, J/cm sec deg K
l = thickness of dry layer, cm
L = thickness of slab, cm
p = pressure, dyne/cm^2
p_o = normal saturation pressure, dyne/cm^2
q = heat flux, J/cm^2 sec
Q = isosteric heat of adsorption, J/g
t = time, sec
T = absolute temperature, deg K
v = velocity, cm/sec
x = variable, cm

Greek Letters:

α = coefficient of linear thermal expansion, cm/cm deg K
β = constant, 0.000178 J/cm^2 sec (deg K)$^{5/4}$
δ = fraction of vapors readsorbed, dimensionless
ϵ = effective porosity, cm^3/cm^3
η = viscosity, g/cm sec (poise)
κ = permeability, cm^2
Λ = thickness of moisture clog, cm
ν = Poisson's ratio, dimensionless
ρ = density, without subscript: bulk density of solid (adsorbent), g/cm^3
σ = Stefan-Boltzmann constant, 5.67 $\times$ 10^{-12} J/cm^2 sec (deg K)^4
σ_f = fracture stress, dyne/cm^2
τ = thermal fire endurance, hr
φ = volume of adsorbate per unit volume of adsorbent, cm^3/cm^3
ψ = figure of merit of moisture, defined by Eq 11, dimensionless

Subscripts:

atm = atmospheric
av = average
c = of moisture clog
d = in dry condition
= of the furnace; representing standard fire exposure
l = at $x = l$
o = at $x \gg L$; when $t = 0$
s = of the surface
w = of water
φ = at moisture content φ

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DISCUSSION

C. C. CARLSON[1] AND M. S. ABRAMS[1]—ASTM Committee E-5 has long wrestled with the problem of moisture and its proper handling with respect to fire tests and fire endurance evaluation. Some of the concepts presented in the paper may provide the answers that Committee E-5 is seeking.

The author's moisture clog concept and the formation of a moisture laden layer behind the fire exposed surface of concrete seems to provide a plausible explanation for a phenomenon we have observed in fire tests of unrestrained, pretensioned-prestressed beams. In such tests, where the beams were naturally dried initially to 70 per cent RH in the deepest section (as required by the standard), we have seen liquid water exuding from the ends of the twisted wire prestressing strands. The water apparently followed the small channels available between the wires. The strands had, in these instances, a minimum concrete cover of 2 in. On other occasions we witnessed liquid water being discharged under considerable pressure into the hot furnace from fine cracks and surface blemishes on the beams. It appears, however, that when a concrete specimen is dried to an equilibrium relative humidity of 70 per cent, the condensation and reevaporation process is such that dangerous steam pressures are not likely to develop. The absence of spalling would seem to indicate that the drying of the concrete to the stated equilibrium relative humidity has produced a pore structure having the proper permeability for the resulting fractional pore saturation to prevent a moisture clog buildup. We have observed, though, that the danger of spalling due to thermal stress (thermal spalling) is present when there is heavy restraint of thermal expansion. In some instances (thin slabs within a heavy restraining frame) the spalling, if one could call it spalling, has been sufficiently violent to fail the specimen in a single occurrence.

The concept of referring actual fire test results obtained at an arbitrary moisture condition to any desired in-service condition is indeed useful. To accomplish this the author notes: (1) The φ value of the material under the expected service conditions must be determined, (2) The moisture content and properties of the material necessary for evaluating the constant b in Eq 20 for the required in-service conditions must be known to calculate the corresponding τ_φ, and (3) The actual fire test should be conducted on a specimen which has been conditioned in a manner such as to produce a microstructure within the component material which compares with that of similar material after several years of service. It appears to us that the determination of the proper microstructure of the material and the suggested method for realizing it may entail some difficulties. However, these difficulties are not

[1] Manager and senior research engineer, respectively, Fire Research Section, Research and Development Laboratories, Portland Cement Assn., Skokie, Ill.

insurmountable. The suggested procedure of storing concrete in an atmosphere at 40 to 50 C and 95+ per cent RH for 30 or more days might serve as a first approximation of the desired end for most concrete mixes and types. In some recent work done at the Portland Cement Association Laboratories, a 3 by ft by 6 in. thick, normal weight concrete slab, moist cured for seven days at 73 F, followed by drying in air for 21 days at 50 per cent RH at 73 F, was subsequently exposed to air in a kiln at 85 per cent RH and 150 F (65.5 C) for 2.1 months. The latter treatment was considered productive of a moisture condition in the cooled slab which would be in equilibrium with air at 73 F and approximately 75 per cent RH. The conditioning procedure did produce a fairly uniform humidity gradient of 75 per cent through the section which compared closely with the distribution of moisture obtained in a companion slab of the same concrete naturally conditioned at 35 per cent RH and 73 F for 3.6 months. The fire endurance of the naturally dried slab was 186 min. This compares with 178 min for the slab conditioned at 85 per cent RH and 150 F. The depression of only 8 min in the fire endurance indicates that the microstructure and moisture condition of the specimen conditioned at 85 per cent RH and 150 F was not greatly different from that of naturally dried (35 per cent RH and 73 F) concrete. Other drying methods which made use of temperatures to 200 F and a very low RH or, that even involved subsequent rewetting treatments produced depressions in the fire endurance of as much as 20 min.

In conclusion, we would like to congratulate the author for his fine contribution to the field of fire research. His approach to the problem of assessing fire resistance of constructions as they will actually be used is in strict conformity with the main purpose of ASTM Method E 119. He has shown that the formidable difficulties of determining moisture effect on the fire resistance of materials can be attacked analytically to produce very useful engineering information. Undoubtedly, other variables affecting fire resistance will also yield to analytical methods.