Prediction of Fire Endurance of Concrete Masonry Walls

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PREDICTION OF FIRE ENDURANCE OF CONCRETE MASONRY WALLS

by G. Williams-Leir and L. W. Allen

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ABSTRACT

The constants in an idealized heat flow simulation are adjusted by non-linear regression to match the experimental results of 94 fire endurance tests performed at the Division of Building Research. They are then used to predict fire endurances. Confidence limits are assigned.

SOMMAIRE

Les constantes d'une simulation idéalisée du flux de chaleur sont ajustées par régression non linéaire de façon à correspondre aux résultats expérimentaux de 94 essais de résistance au feu effectués par la Division des recherches en bâtiment. Elles servent alors à prédire la résistance au feu. On établit les limites de confiance.

NATIONAL RESEARCH COUNCIL OF CANADA
DIVISION OF BUILDING RESEARCH

PREDICTION OF FIRE ENDURANCE OF CONCRETE MASONRY WALLS

by

G. Williams-Leir and L. W. Allen

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of the
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November 1973

PREFACE

In the light of new experimental work, it was necessary to update the tables for a new edition of Supplement No. 2 to the National Building Code of Canada, that specify the conditions under which walls of certain types of construction are deemed to comply with certain fire resistance stipulations. One of the authors, L.W. Allen, who held a Concrete Fellowship with the Division of Building Research, had performed fire tests on walls of many types of concrete block construction. The process by which new tables were derived from these tests for submission to the Associate Committee on the National Building Code is one that should be a matter of public record, so that it may be subject to informed criticism. This report is detailed for that reason. The tests themselves are more fully described in References 1 and 2.

Ottawa
November 1973.

N.B. Hutcheon,
Director.

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PREDICTION OF FIRE ENDURANCE OF CONCRETE MASONRY WALLS

by

G. Williams-Leir and L.W. Allen

At the Fire Laboratory of DBR/NRC fire tests of walls and floors are conducted in accordance with the methods and criteria of ASTM E119-69, 'Standard Methods of Fire Tests of Building Construction and Materials' (3). This standard specifies the intensity of the fire, the size of specimen, and the criteria for determining the end point of the test. In the case of walls, the criteria are: (a) collapse of the structure; (b) excessive temperature rise on the unexposed surface; and (c) the development of cracks in the structure through which flames or hot gases may pass. For certain types of structure, experience has shown that fire endurance is normally determined by criterion (b); in such cases, a small-specimen fire test will give comparable data on the thermal fire endurance of a structure.

In the absence of either a standard or a small-specimen test, the fire endurance of some structures may be estimated through analysis of existing fire test data on other structures similar in some but not all respects to those for which performance is to be estimated. It is possible to interpolate and extrapolate test results and in this way extend the range of structures to which they can be applied. This paper describes a series of 94 fire endurance tests on various unit masonry walls, and presents results of the statistical procedures used to establish the fire performance of most possible types of concrete masonry walls.

Another report (4) describes empirical formulae fitted to most of the same fire test results. Those wishing to interpolate estimates of fire endurance will probably find these formulae simpler to apply than the procedures used in this paper.

FIRE RESISTANCE TESTS ON MASONRY ASSEMBLIES

The fire test series upon which the analysis is based was initially planned to develop information on the fire performance of concrete blocks characteristic of Canadian production. Sixty-nine types of blocks were included in the program, from which 94 specimens were built and subjected to fire exposure. Sixteen of the tests were carried out on standard specimens in strict accordance with the requirements of ASTM E119-69. In the remaining 78 tests the procedures of ASTM E119-69 were generally followed except that they were conducted on smaller specimens. For these tests fire endurance periods were determined solely by the criteria for temperature rise on the unexposed surface. All specimens were subjected to the standard fire exposure described by the time-temperature curve given in ASTM E119.

Variables investigated in the test series included size and geometry of masonry unit, type of aggregate in the unit, method of curing, influence of plaster protection and the effect of sand replacement on the fire endurance of lightweight aggregate units.

Standard Fire Endurance Tests

Standard test specimens measured approximately 10 ft by 12 ft and were mounted in a precast concrete restraining frame to restrict expansion during fire exposure. Specimens were deemed ready for test when the interior or dampest section of the assembly had achieved a moisture content corresponding to equilibrium with air in the range of 50 to 75 per cent relative humidity at 73 ± 5°F.

Immediately following fire exposure the test assembly was moved away from the furnace and a hose stream was directed at the hot surface of the specimen. The nozzle pressure and duration of application of the hose stream were as specified by the Standard Method in relation to the period during which the construction continued to function as an effective barrier against fire, i.e., 30 or 45 lb/sq in. and 1 to 6 min of application. All specimens withstood the hose stream test without breakthrough of the water stream.

Failure of eleven of the standard specimens during fire exposure was due to the average temperature on the unexposed surface exceeding the allowable limit (250°F above ambient temperature). The remaining five failed by excessive temperature rise at individual points on the unexposed surface (325°F above ambient). There were no failures due to either collapse or to the development of large cracks in the structure.

Small Specimen Fire Tests

Although fire tests of small specimens are generally restricted to exploratory work in the development of new materials or assemblies, considerable emphasis was placed on their value in planning the fire test program. Several reasons may be given for their inclusion: (a) Small-specimen tests give reliable and comparable data on the temperature history of the unexposed surface of various materials or assemblies. In the case of masonry assemblies, which seldom fail by collapse of the structure, it is the temperature history of the unexposed surface that is of primary interest. (b) The relationship between fire endurance of similar constructions as determined from both standard and small-specimen tests was studied experimentally, and the effect of specimen size was taken into account during analysis of the data. (c) The relatively low cost of small-specimen tests permitted a much wider range of variables in planning the test program.

Small specimens measured about 2 1/2 ft square; they were not restrained during the fire test. Relative humidity within specimens was monitored prior to testing and specimens were subjected to fire exposure when moisture levels as required by ASTM E119-69 had developed. Small specimens were not loaded during the test and were not subjected to the hose stream test following fire exposure. Sixty-four of the 78 small specimens failed by average temperature rise on the unexposed surface, and the remaining 14 by temperature rise at individual points.

MATERIALS

Six types of aggregate were used in the concretes represented in the series: two normal-weight or dense - siliceous and calcareous, 27 tests; and four lightweight - pumice, expanded slag, expanded shale, and expanded clay, 67 tests. In 35 of the latter the aggregate was diluted by up to 60 per cent by bulk volume of siliceous or calcareous sand replacement.

The blocks made from these concretes were of the following nominal thicknesses:

4 inch - 55 tests
6 inch - 33 tests
8 inch - 4 tests
10 inch - 2 tests

Each was nominal 8 in. high and nominal 16 in. long. Forty-nine of them were hollow with either two or three cavities from top to bottom. Nine of the siliceous concretes and two of the expanded slag concretes had been cured under pressure, i.e., autoclaved. For these the composition was modified, as described in Fire Study 25 (1). Seven of the test walls built from these blocks were finished with 5/8-in. gypsum plaster on each side. The moisture contents ranged from 1 to 17 per cent by volume.

METHOD

The methods used in this study differ only in detail from those described in another report on the correlation of 107 fire tests on monolithic concrete slabs (5). Given a large table of results of numerically simulated fire tests, regression is used to determine, for each material, those properties ('notional thermal properties') necessary in a simulation for the results to match the experimental results as closely as possible, assuming that failure will always be by criterion (b), mentioned earlier, i.e., by thermal conduction.

The regression determines the constants in equations that correlate these properties with the data that is taken as determining them: i.e., density within each material type for the slabs and sand replacement within each material type for these blocks.

In the former case both diffusivity and specific heat were taken as explicit functions of density, the constants for each material in the expressions being determined by non-linear regression. Conductivity was taken as the product of these and the experimental density.

In the present work, each concrete was regarded as a two-phase mixture of cement paste and aggregate, or as a three-phase mixture of these with sand. As such its specific heat per unit volume was calculable from those of its components, and its conductivity could be found by methods to be described in the next section. Diffusivity was the ratio of these quantities. The thermal properties, conductivity and specific heat per unit volume, of the individual phases were the unknowns that were determined by regression. It was initially intended to find the proportion of cement paste by regression, but after indications of instability this was fixed at 25 per cent.

This study presented rather more difficulty than that on slabs (5), because of the larger number of independent variables.

CONDUCTIVITY OF MULTIPHASE MIXTURES

The literature provides several methods of calculating the conductivity of a two-phase mixture. It was found that, in the range with which the present work is concerned, there is not much to choose between the results found by the methods proposed by Bruggeman (see reference 6), Hamilton (7) and Woodside (see reference 8). Hamilton's method produced results lying between those of the other two and was therefore adopted.

In principle, the conductivity of a mixture of p phases can be calculated as for two phases, one discrete and one continuous, the latter being a mixture of p-1 phases, and thus by repeated application from the properties of the individual phases. In general, however, it is found that the result depends upon the order in which the discrete phases are taken. Since the logic of this procedure depends on taking a mixture of two phases of different conductivities, one of which is discrete, as continuous it seems appropriate to choose the discrete phases in the order that least violates this precondition, i.e., to choose first that discrete phase whose conductivity is nearest to that of the continuous phase.

The result of any such procedure must be regarded as an empirical approximation. It exhibits a discontinuity when the conductivity of a discrete phase is varied so as to become or cease to be the nearest to that of the continuous phase.

PLASTERED WALLS

Seven of the walls tested were finished on both sides with 5/8-in. gypsum plaster; some additional complication was unavoidable if these were to be included in the present study. Conductivity and specific heat for plaster alone were two constants to be determined by regression; for the composite wall, the over-all conductivity and specific heat were calculated from those of the laminae. For diffusivity it was necessary to treat the wall as though it consisted of a great number of thin laminae of concrete alternating with plaster so that the thermal properties would be uniform across the section.

EFFECT OF CAVITIES IN HOLLOW BLOCKS

It is reasonable to suppose that to a first approximation a hollow block behaves like a solid one of smaller over-all thickness if there are equal quantities of concrete in each. There are two methods of determining equivalent thickness. The established method is described in ASTM C-140 (9), but the method used throughout this investigation was the 'lead shot method' described by Allen and Harmathy (10).

To a second approximation, it is plausible that hollow blocks have some advantage over solid ones of equal equivalent thickness. Harmathy (11) has given reasons for expecting that, for a given quantity of concrete, it should be advantageous to have as much as possible in the face shell and as little as possible in the web. A dimensionless ratio V (for volume ratio) has accordingly been introduced representing the ratio of the cross-sectional area of the face shell to the cross-sectional area of the corresponding web.

$$V = b\ell/a\,(Z-2\ell)^{*} \qquad (1)$$

---

* See nomenclature at end of text.

Figure 1 shows where these measurements are taken.

For solid blocks V is conventionally set at zero. It ranged from 0.94 to 3.12 over the hollow blocks used in these experiments.

At the ends of each block there is an enhanced local equivalent thickness owing to the contiguity of two end webs. Thermally the weak point of a hollow block is between webs (11); if they are not all equal then it is nearer to the thinner webs. The expression for volume ratio was accordingly designed to correlate the thermal performance with the geometry of the most vulnerable part of a block midway between two thin webs. For blocks with only one core, the web thickness would be taken as the combination of two end webs plus mortar.

Volume ratio would be an inappropriate parameter for constructions where there was no connection between two wythes of a wall, or much less than in conventional concrete blocks.

MOISTURE

Moisture undoubtedly has a substantial effect on the experimental results. Harmathy's study of this (12) leads to expressions equivalent to:

$$Te = Td\,(1 + BM/(1 + Td/4)) \qquad (2)$$

where
- Te = fire endurance at M,
- Td = fire endurance when dry,
- M = volumetric moisture content, cm^3 water/cm^3 material
- B = a function of permeability.

It was initially intended to use the published values of B, and thus keep down the number of constants to be determined by regression. This led, however, to anomalous results, and it was then decided to preserve the form of the expression but allow B to be determined by regression. The two values found, for dense and for lightweight concrete, were substantially smaller than those published.

The regression was of endurances thus corrected to the dry condition. Predictions from it were then reconverted to the standard condition of equilibrium with 75 per cent relative humidity (3) by the same method.

It may be noted that this procedure is different from that adopted for the 107 monolithic slabs, where the data was corrected to the standard condition before regression, so that no subsequent reconversion was necessary. It is not known which of these procedures is preferable.

For the 28 specimens described in (2), measurements of moisture content at the time of test were not available, and values were estimated on the basis of sand replacement.

CONSTRAINTS

Misleading indications can arise from an investigation such as this, especially since it was not statistically designed. The onus is on the investigator to so constrain the study that invalid conclusions are, as far as possible, excluded.

(1) For dense concretes, the gradients of endurance against thickness were dominated by a small number of tests on thick blocks. Test No. 13 suggested that, contrary to experience, calcareous concrete was inferior to siliceous for blocks over 5 inches equivalent thickness. To avoid an invalid distinction these two concrete types were treated as one.

(2) The evidence of a distinction between siliceous and calcareous sand was not clear, and these were also treated as one material. There was, however, a substantial difference between the thermal properties of these sands and those of the dense aggregates. This reflects the observation that at 60 per cent sand replacement none of the light-weight aggregates gave much better performance than dense concrete, and some of them were worse at 40 per cent.

(3) The data pointed to a complicated interaction between scale, density, and volume ratio V, that would be hard to rationalize. It was decided to make the effect of scale of test independent of the other factors; and to allow the coefficient of V to depend on whether the aggregate was dense or lightweight, provided it was not negative for either group.

WEIGHTING OF DATA

It was thought that fire tests of long duration tend to give more reliable information than short ones, so each point was weighted in proportion to the square root of experimental fire endurance. So that the seven plastered walls which had much higher fire endurance would not unduly influence the result, their weights were halved. Standard tests were given twice the weight of small-specimen tests.

COMPUTATION

Regressions were performed by means of a routine POZMIN, (13). This uses Powell's method (14) as modified by Zangwill (15), to minimize $\underline{F}$, by adjustment of the unknowns $\underline{a}$

$$F = \sum_{i=1}^{m} w_i f_i^2 \qquad (3)$$

where w_i is a weighting factor and, for the present problem,

$$f_i = \log {}_i\hat{T} / {}_iT \qquad (4)$$

where $_{i}T$ is the i^{th} of m fire endurances, and $_{i}\hat{T}$ is the corresponding prediction, a complicated function of $\underline{a}$ and the measurable properties. The results are given in Table 1.

Having found an acceptable procedure for non-linear prediction, the next step is to perform a linear regression of log T upon log $\hat{T}$. This provides coefficients, a standard error $\underline{s}$, and an inverse matrix, $\underline{C}$, needed for the calculation of confidence limits.

CONFIDENCE LIMITS

Each regression equation provides a 'best estimate' in the least squares sense, i.e., its prediction has equal chances of lying below or above the true value. That is to say, the user of the information stands an even chance that it will deceive him, that a construction for which he has calculated a prediction will in fact fail before the end of the calculated period. In effect, the confidence level of the prediction is 50 per cent.

In situations where the safety of life and property is involved, as they are in fire protection, it is clearly desirable to work at a higher confidence level.

The situation would be no different if one was given simply the average of a number of results of fire tests upon identical constructions; one would have no more than 50 per cent confidence that a future test on the same construction would equal or exceed the average. However, given the results of the individual tests and assuming they fit some distribution, it is a simple matter to calculate a fire endurance in which one could have 90 per cent or any other level of confidence $100\,(1 - \alpha/2)$ per cent (16).

The same thing can be done with the prediction derived from a linear regression equation, although the calculation is more laborious (17). It is necessary first to assume that the distribution of discrepancies is symmetrical Gaussian. From the right-hand side of the linear regression equation Eq. (13) below, a term:

$$Q = t\,\{(m-n),\ (1-\frac{\alpha}{2})\}\ s\sqrt{1 + X_o' C X_o} \qquad (5)$$

(which will be referred to as the 'confidence band width') must be subtracted before the equation is solved for T*. The result is then the 'lower 10 per cent point' T_{10}, a fire endurance time such that 90 per cent of future tests can be expected to yield $T > T_{10}$, and only 10 per cent $T < T_{10}$. An upper 10 per cent point could be similarly calculated, if needed, by adding Q. The result would be T_{90}, such that 10 per cent of future tests might be expected to yield $T > T90$.

This procedure has been used in the calculation of Figure 2 and Table 2.

DETAILS OF PREDICTION PROCEDURE

For the individual components, conductivity and specific heat per volume are:

$$k = a_{(2N_{ag}-1)} \qquad (6)$$

$$\rho c = a_{(2N_{ag})} \qquad (7)$$

where N_{ag} has values from 1 through 8, corresponding to slag, shale, clay, pumice, siliceous or calcareous, plaster, sand, and cement paste respectively.

Equivalent thickness is modified for volume ratio as follows:

$$E = L\,(1 + V\,(a_{18}\,N_c + a_{19}\,(1-N_c))) \qquad (8)$$

where $N_c = 1$ if $N_{ag} = 5$, otherwise $N_c = 0$.

Experimental fire endurance is corrected for moisture content.

$$C_z = 0.5\left\{4 - Te + 4M\,a_{(N_c + 22)}\right\} \qquad (9)$$

$$T_d = (C_z^2 + 4T_e)^{1/2} - C_z \qquad (10)$$

Conductivity k and specific heat per volume ρc for each concrete are functions of the properties of the components and of their proportions. For plastered concrete, these properties are similar functions.

$$K = k/\rho c$$

$$x = \log_{10}(E^2/K) \qquad (11)$$

$$z = E/k$$

y = function of x & z interpolated from table made by spline-fitting the heat flow simulations.

[The simulation table contains 31 x 49 entries each of four digits.]

$$\hat{T} = (1 + (1 - S_c)\alpha_{21})\,(1 + \alpha_{20}\,A_c)\,E^2/Ky \qquad (12)$$

This completes the non-linear procedure.

Linear regression now yields:

$$\log_{10} T^* = -0.00156 + 1.0027 \log_{10} \hat{T} \quad (13)$$

$$s = 0.03827$$

$$C = \begin{bmatrix} .04769 & -.1046 \\ -.1046 & .2953 \end{bmatrix}$$

from which confidence limits may be calculated.

EFFECT OF PLASTER

The best simple generalization regarding the effect of plaster that has so far been derived from this work is as follows.

For walls of dense concrete, an added 5/8 inch of plaster on each face at least doubles the fire endurance. For walls of lightweight blocks up to four hours, a similar finish adds at least one hour. Sanded lightweights are intermediate between these extremes.

COMPARISON BETWEEN PREDICTIONS AND THE EXPERIMENTAL RESULTS

It is not necessary to tabulate the predictions that substantially agree with experimental results, since the latter are given in detail in References 1 and 2.

All the tests for which the experimental results fell outside the confidence band are given in Tables 3 and 4. On each side, below and above, the expected number outside the band is 10 per cent of 94. In fact six are found below and eleven above.

COMPARISONS WITH OTHER WORK

Published fire tests on concrete masonry walls (18 to 22) and unpublished tests on vertical slabs (23) have been compared with the confidence limit in Table 5. Various differences in the condition of test, notably moisture, have not been allowed for. Seventy-three tests by Menzel (24) have been excluded from this Table on the grounds that his results appear to be on the low side, perhaps because many of them are small-scale tests on experimental concretes not representative of practice. Small-scale results by Galbreath (23) have been retained, although they too tend to be lower than the predictions. Eight of the 24 tests had less fire endurance than the confidence limit, but only one prediction overshot by more than nine minutes. The discrepancy of nearly three hours for a 10-in. pumice block suggests that this material is more variable than the others.

NOMENCLATURE

a	web thickness, feet
a	(with subscript) unknown determined by regression; constant in non-linear regression equation
A_c	1 for autoclaved concrete, 0 for regular-cured concrete
b	web spacing, feet
B	a function of permeability (see section on moisture)
c	notional specific heat (Btu/lb R)
c_z	intermediate in solution for T_d
C	the (n x n) inverse matrix $(X'X)^{-1}$
E	equivalent thickness modified by volume ratio, feet
f	discrepancy between experiment and prediction (see equation 3)
F	sum of squared discrepancies (equation 3)
k	notional conductivity (Btu/ft h R)
K	notional diffusivity (ft^2/h)
ℓ	face shell thickness, feet
L	equivalent thickness, feet
m	number of observations (94)
M	volumetric moisture content, cm^3 water/cm^3 material.
n	number of regression coefficients
N_{ag}	serial number distinguishing aggregate types
N_c	1 for dense concretes, 0 for lightweights.
Q	confidence band width
s	standard error of estimate
S_c	scale (0 = small, 1 = large)
t	refer to statistical tables for the t-distribution
T	fire endurance, hours
$\hat{T}$	non-linear prediction, hours
T^*	linear prediction, hours
V	volume ratio, face to web = $b\ell/a(Z-2\ell)$

w	weighting factor
x	argument of simulation table
X	the (m x n) matrix of observations
X'	transpose of X
X_o	vector of the n predictors at the point of interest
y	value from simulation table
z	argument of simulation table
Z	actual thickness of hollow block, not including plaster, feet

Greek

α	probability of a result outside the upper or the lower confidence limit
ρ	density, $lb. ft^{-3}$

Subscripts

d	for dry specimen
e	experimental
i	serial number of observation
j	serial number of regression variable

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TABLE 1

VALUES ASSIGNED BY REGRESSION

	(Notional) Conductivity Btu/h ft R	Specific heat per unit volume Btu/ft^3 R
Expanded slag	0.1942	10.01
" shale	0.8483	72.84
" clay	0.1801	8.761
Pumice	0.1192	4.173
Sil or Calc agg.	1.353	89.16
Plaster	0.3846	31.34
Sand	1.938	84.31
Cement paste	0.7349	74.68

Coefficient of volume ratio for dense concretes	0.01749
" " " lightweight concretes	0
" for autoclaving	-0.07168
" " scale	0.02826
" " moisture content for dense concretes (B)	0.8019
" " " " " lightweight concretes	3.015

TABLE 2

MINIMUM EQUIVALENT THICKNESSES

(as measured by lead shot method, of concrete blocks, for 90% confidence of attaining specified fire endurances, when at equilibrium with 75% RH.)

	% Sand	E.T. in inches for fire endurance of 0.5	0.75	1	1.5	2	3	4 hours
	0	1.64	2.11	2.50	3.11	3.62	4.42	5.05
Expanded	10	1.63	2.11	2.50	3.14	3.66	4.51	5.19
Slag	20	1.64	2.11	2.52	3.19	3.73	4.62	5.34
	30	1.64	2.15	2.56	3.25	3.82	4.75	5.52
	0	1.46	2.02	2.48	3.23	3.80	4.80	5.64
Expanded	10	1.49	2.06	2.54	3.33	3.90	4.94	5.81
shale	20	1.52	2.10	2.59	3.42	4.00	5.08	5.98
	30	1.55	2.13	2.65	3.51	4.11	5.22	6.15
	0	1.64	2.11	2.48	3.09	3.59	4.37	4.99
Expanded	10	1.62	2.09	2.48	3.12	3.63	4.46	5.13
clay	20	1.63	2.10	2.51	3.16	3.70	4.58	5.29
	30	1.64	2.14	2.54	3.23	3.79	4.71	5.47
	0	1.59	2.02	2.37	2.94	3.39	4.09	4.64
Pumice	10	1.56	2.01	2.37	2.96	3.44	4.20	4.80
	20	1.56	2.02	2.40	3.01	3.51	4.33	4.98
	30	1.59	2.04	2.44	3.09	3.62	4.48	5.19
Siliceous	0	1.68	2.29	2.84	3.71	4.39	5.55	6.52
or	0	1.62	2.21	2.74	3.58	4.25	5.36	6.30
Calcareous*	0	1.72	2.34	2.88	3.74	4.43	5.59	6.56

* of the three rows of figures for siliceous/calcareous concretes, the first relates to solid blocks, the second to hollow ones, and the third to autoclaved hollow blocks.

"Hollow" here means "having volume ratio not less than 2."

TABLE 3

EXPERIMENTAL RESULTS BELOW THE LOWER CONFIDENCE LIMIT OF PREDICTION

Test number	14	37	7	8	13	25
Scale	L	L	S	S	S	S
Aggregate type	5	3	4	4	6	4
Sand replacement per cent	-	9.1	-	12.8	-	-
No. of cores	2	2	2	2	-	-
Thickness: over-all in.	3.64	5.62	5.63	5.66	5.59	3.65
equivalent in.	2.71	3.19	3.33	3.33	5.59	3.65
Autoclaved ?	n	n	n	n	n	n
Moisture content per cent by volume.	2.89	7.21	9.63	11.65	4.00	16.76
Density lb. ft^{-3}	128.7	90.9	81.2	90.1	133.8	77.2
Plastered ?	n	n	n	n	n	n
Volume ratio	2.76	1.43	1.20	1.04	0	0
T experimental hours	0.93	1.57	1.83	2.03	3.00	2.57
predicted "	1.10	1.80	2.36	2.36	3.46	3.17
lower confidence limit "	0.98	1.60	2.10	2.10	3.08	2.83
LCL - Texp.	0.05	0.03	0.28	0.07	0.08	0.26

Key to aggregate types:

1. Expanded slag
2. " shale
3. " clay
4. Pumice
5. Siliceous
6. Calcareous

TABLE 4

EXPERIMENTAL RESULTS ABOVE THE UPPER CONFIDENCE LIMIT OF PREDICTION

Test number	16	29	61	62	24	32	22	40	25	95	96
Scale	S	S	S	S	S	S	L	S	L	S	S
Aggregate type	5	6	6	6	4	4	2	3	4	4	4
Sand replacement per cent	-	-	-	-	-	-	-	-	-	38.3	58.4
No. of cores	2	3	2	2	2	2	-	-	-	-	-
Thickness, over-all in.	5.62	3.62	5.64	5.64	3.61	3.61	3.61	3.63	3.65	3.60	3.61
equivalent in.	3.58	2.74	3.67	3.67	2.74	2.74	3.61	3.63	3.65	3.60	3.61
Autoclaved ?	n	n	n	n	n	n	n	n	n	n	n
Moisture content, per cent by vol.	4.66	5.40	4.20	4.06	3.29	6.24	6.04	8.97	16.76	5.89	4.63
Density $lb.ft^{-3}$	126.5	134.9	133.4	133.4	78.9	78.9	82.9	87.5	77.2	96.2	106.9
Plastered ?	n	n	n	n	n	Y	n	n	n	n	n
Volume ratio	1.71	2.31	1.78	1.78	2.39	2.39	0	0	0	0	0
T experimental hours	1.92	1.38	2.08	2.05	1.67	3.67	2.34	2.88	3.60	2.61	2.20
predicted "	1.70	1.16	1.77	1.77	1.43	3.07	2.06	2.47	3.09	2.16	1.85
upper confidence limit hours	1.90	1.30	1.99	1.99	1.60	3.44	2.31	2.77	3.46	2.42	2.08
Texp - UCL	0.02	0.08	0.09	0.06	0.07	0.23	0.03	0.11	0.14	0.19	0.12

TABLE 5

PREDICTED FIRE ENDURANCE (90% CONFIDENCE) COMPARED WITH REPORTED VALUES

Nominal thickness and design of block: inches/number of cores. (1)	Dimensions of specimen, ft./in. or feet x feet (2)	Aggregate (3)	Equivalent thickness[a] of block, in. (4)	Load during fire test (on gross area), lb/in.^{2} (5)	Experimental fire endurance, hr. (6)	Predicted fire endurance at 90% C.L., hr. (7)	Remarks (8)	Ref (9)
6/3	12x14	Exp. shale	5.08	79	4.05	3.30	-	20
4/sld[c].	11/8sq.	"	3.65	Restrd.[b]	2.02	1.87	-	19
6/3	11/8sq.	"	3.89	"	2.02	2.08*		18
8/3	10x12	Calc.	4.56	80	2.24	2.26*		22
8/3	10x12	"	6.24	175	3.95	3.80	Collapsed at 343 lb/in^2 during re-load test.	22
4/4	8x9	Exp.Slag	2.52	Restrd.	1.45	1.01		21
4/4	8x9	Pumice	2.51	"	1.90	1.11	Moisture content units prior to test = 6.6%	21
4/4	8 sq.	"	2.51	"	1.27	1.11	Moisture content units prior to test = 1.8%	21
6/3	8x10	Exp. Slag	4.56	"	3.30	3.21	Moisture content units prior to test = 2.6%	21
6/3	8x10	"	4.56	175	3.90	3.21	Moisture content units prior to test = 3.8%	21
6/3	8x10	"	4.56	"	3.92	3.21	Moisture content units prior to test = 3.0%	21

TABLE 5 (Cont'd)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
10/3	8x10	Exp. shale	6.00	70	4.70	4.47	-	18
6/3	8x10	Exp.		Rstrd.			-	21
6/3	8x10	Exp. slag	4.56	Rstrd.	3.48	3.21	-	21
6/3	20 ft^2	"	3.66	"	2.42	2.05	-	21
10/3	40 ft^2	Pumice	6.00	"	4.55	7.52*	-	21
10/3	40 ft^2	Exp. shale	6.00	"	4.32	4.47*	-	21
5 1/8 Conc. Slab	2 1/2 Sq.	100 % Carbon-ate	5.13	Un-rstrd	2.75	2.60	Concrete slabs were tested in vertical position according to the methods of test for wall assemblies	23
"	2 1/2 Sq.	100 % Granite	5.13	"	2.78	2.60	"	23
"	2 1/2 Sq.	65 % Quart-zite	5.13	"	2.58	2.60*	"	23
"	2 1/2 Sq.	35 % Granite	5.13	"	2.58	2.60*	"	23
"	2 1/2 Sq.	85 % Quart-zite 15 % Carbon-ate	5.13	"	2.56	2.60*		23
"	2 1/2 Sq.	65 % Quart-zite 35 % Carbon-ate	5.13	"	2.55	2.60*		23
"	2 1/2 Sq.	85 % Quart-zite	5.13	"	2.50	2.60*		23
"	2 1/2 Sq.	100 % Quart-zite	5.13	"	2.47	2.60*		23

* Predicted fire resistance (90 % confidence) exceeds reported value

a Equivalent thickness was determined from reported values of core area for the units.

b Restrained.

c Solid.

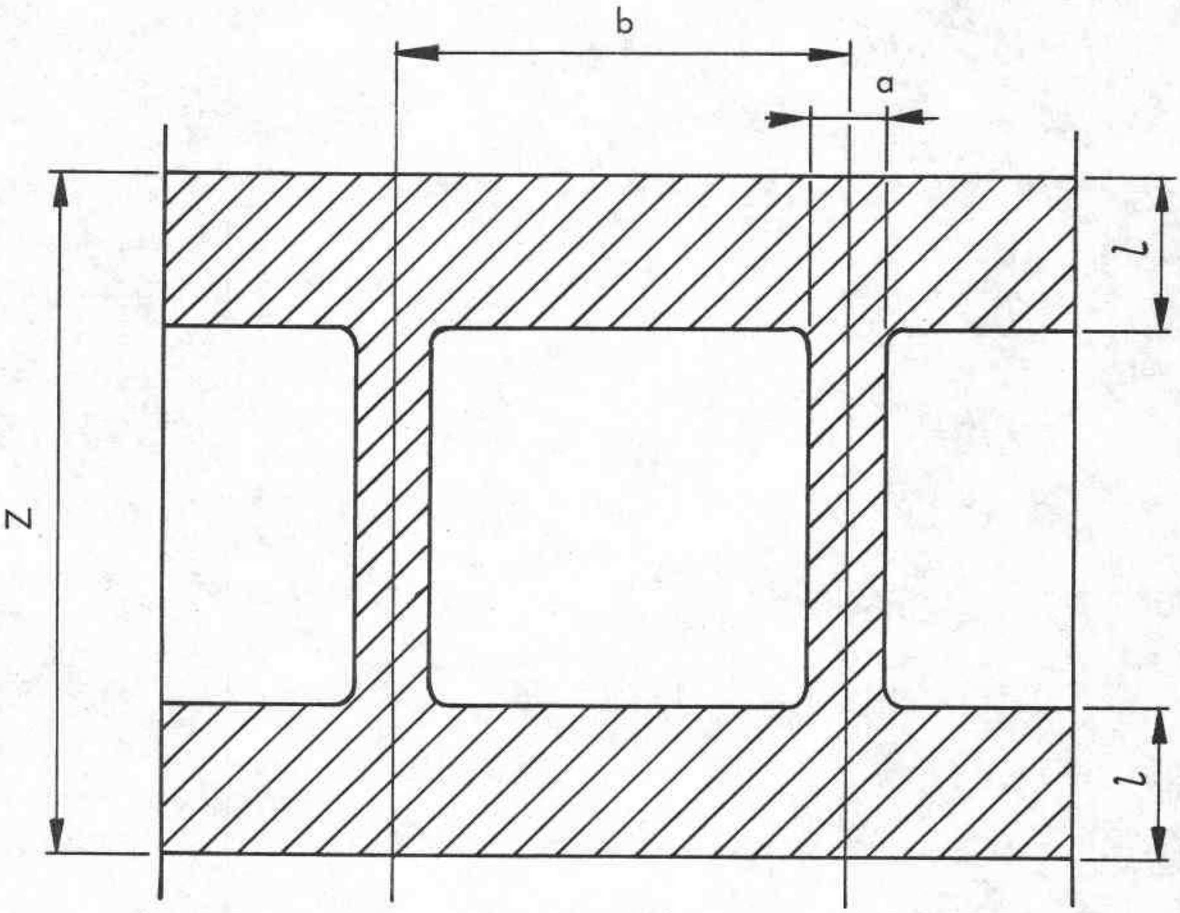

FIGURE 1 THE GEOMETRY OF A CONCRETE BLOCK

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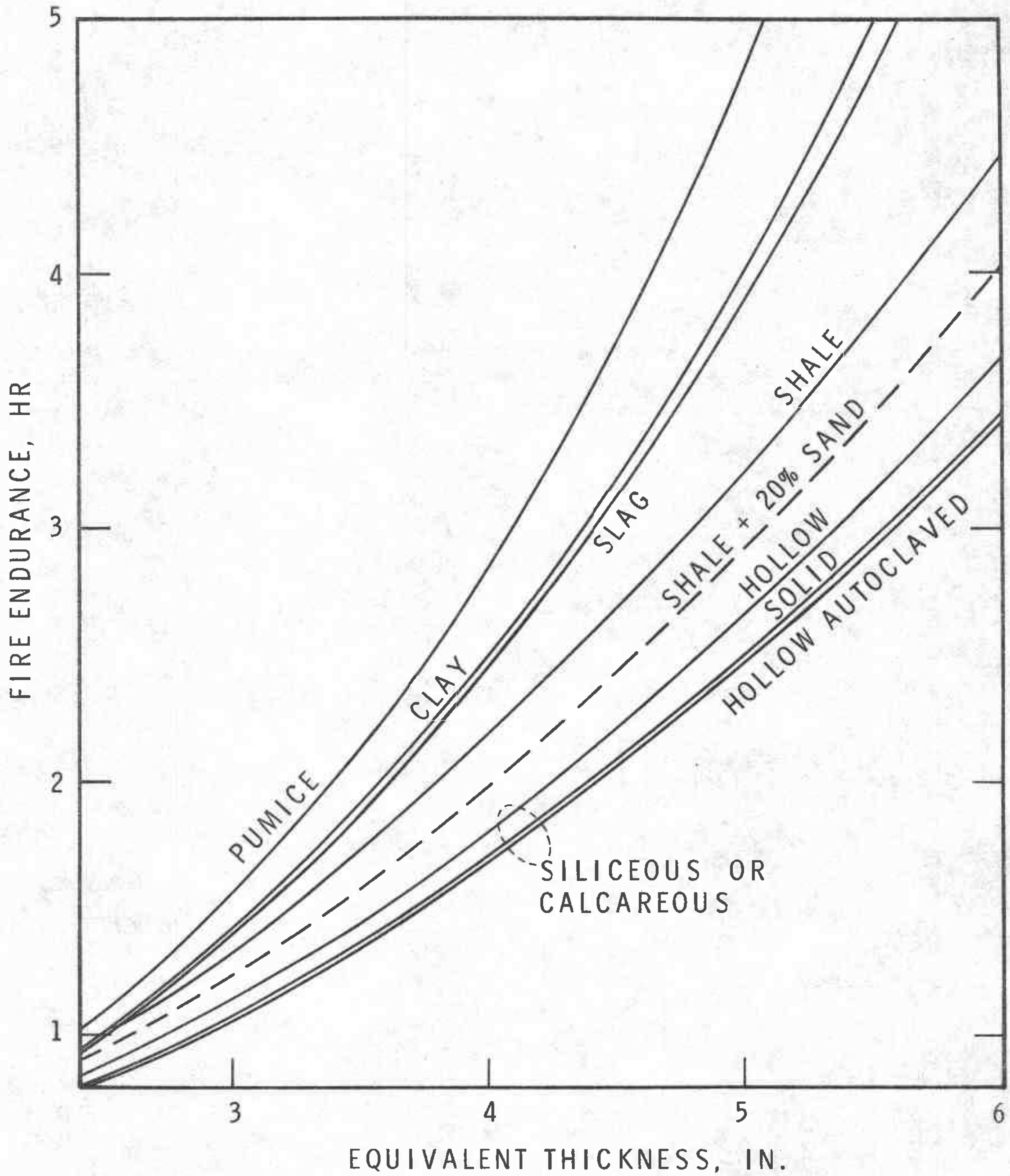

FIGURE 2

FIRE ENDURANCE AT EQUILIBRIUM WITH 75% RELATIVE HUMIDITY. 90% OF FUTURE TESTS ARE EXPECTED TO EQUAL OR EXCEED THESE VALUES

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APPENDIX

Data

Some of the information tabulated was used in preliminary regressions and then discarded, and only the following parameters were used in the regressions reported.

Scale of test

Type of principal aggregate

Sand replacement, per cent by volume. Information from block manufacturer.

Over-all thickness of block: mean of 5 measurements by a commercial testing laboratory.

Equivalent thickness: as determined at DBR by the lead shot method (10). [Much preliminary work was done with equivalent thickness determined in accordance with ASTM C-140 (9), but all work reported here is on the other basis. Plaster not included in these measurements]. Further details may be found in the original reports (1, 2).

Face shell thickness for hollow blocks: mean of 5 measurements by a commercial testing laboratory.

Plaster: 5/8 in. of gypsum-sand plaster applied to each side of the wall, as described in (1).

Fire endurance, hours, determined in the 94 tests described.