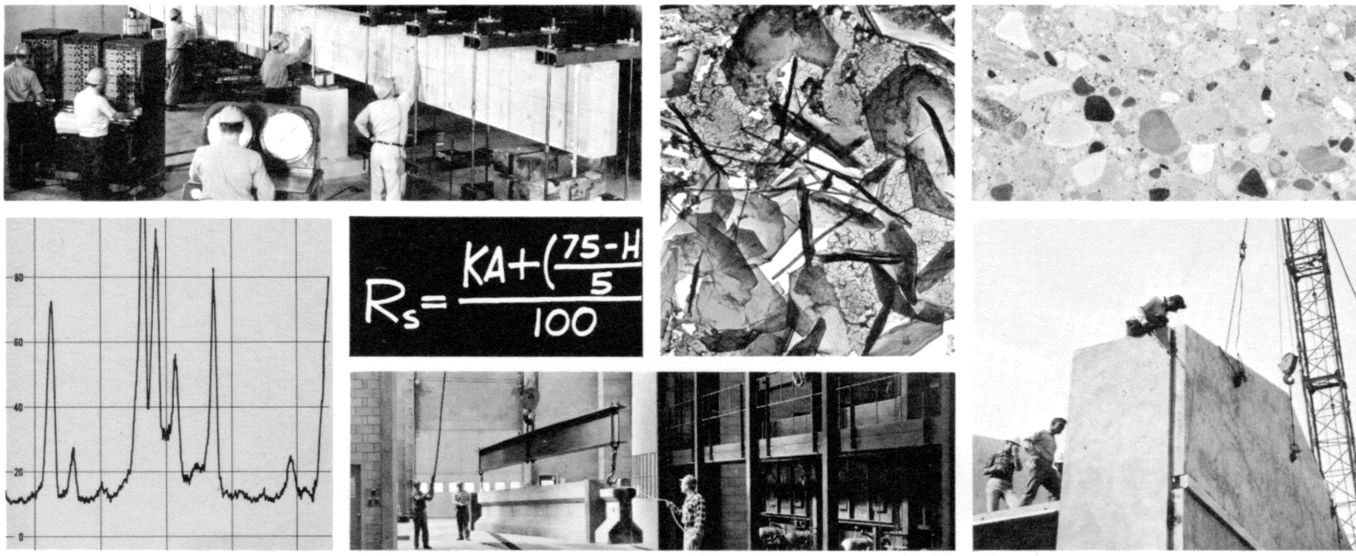
RESEARCH AND DEVELOPMENT BULLETIN



Fire Resistance of Lightweight Insulating Concretes

By A. H. Gustaferro, M. S. Abrams,
and Albert Litvin

PORTLAND CEMENT ASSOCIATION

Fire Resistance of Lightweight Insulating Concretes

By A. H. Gustaferro,
M. S. Abrams, and Albert Litvin*

SYNOPSIS

This report presents data on the fire resistance of concretes having oven-dry unit weights in the range of 30 to 100 pcf. Relationships between slab thickness and fire endurance, based on 250 F rise of the unexposed surface, are given for concretes with various unit weights. Data are also presented on temperature rise of the unexposed surface and temperature distribution through the slabs during fire tests. Design charts for estimating the fire endurance of two-course floors and roofs are discussed, and relationships between moisture content and relative humidity of fire test specimens are presented.

Key Words: cellular concretes, concrete slabs, fire resistance, fire tests, floors, insulating concretes, perlite, roofs, thermal insulation, vermiculite.

INTRODUCTION

This is the third of a planned series of reports on the fire endurance of concrete slabs as determined from fire tests of 3x3-ft** specimens. The first report(1)† deals with single-course slabs made of structural concretes and the second(2) with two-course floors and roofs. This report presents the results of 39 fire tests of slab specimens 2 to 5 in. thick. Twelve of the tests, which were on concretes with oven-dry unit weights of about 30 pcf, were reported previously.(2)

ACI's "Guide for Low Density Precast Concrete Floor, Roof, and Wall Units"(3) states that "the fire retardant functions of low density concrete range from that of supporting loads during and after a fire to that of significantly reducing heat transfer." This report deals with the latter function.

---

*Manager and Principal Research Engineer, Fire Research Section, and Manager of Construction Research Section, respectively, Research and Development Division, Portland Cement Association, Skokie, Ill.

**Equivalent metric units may be obtained by using conversion factors shown on page 5.

†Superscript numbers in parentheses designate references on page 6.

TEST PROGRAM

Description of Specimens

All fire test specimens were 3x3 ft in plan and had nominal thicknesses of 2, 3½, and 5 in. As in previous studies,(1) chromel-alumel thermocouples and humidity wells were embedded in the slabs at various depths.

Materials

Cellular, perlite, and vermiculite concretes having oven-dry unit weights of 30 to 100 pcf were included in the study. Data on the 11 mixtures are given in Table 1. Cellular concretes were made with preformed foam, while perlite and vermiculite concrete aggregates were used for the other concretes. Variations in unit weight were achieved by additions of sand. In one mix, V-70, expanded shale aggregate was used. Aggregate gradations are given in Table 2.

Mixing

Concrete was mixed in a paddle-type mixer. For each type of concrete a particular sequence of batching and duration of mixing was maintained:

1. For the cellular concretes, water, cement and sand (if used) were mixed together for 1 to 2 minutes until a uniform slurry was formed; the preformed foam was then added without stopping the mixer and mixing was continued for an additional 1½ minutes. The foam was formed from a 4 percent solution of hydrolyzed protein-type foaming agent in a generator consisting of a pressure tank, pickup assemblies, and foam nozzle.
2. For the perlite concretes, water, air-entraining agent, and cement were mixed together for 1 to 2 minutes before sand (if used) was added and mixed for 1 to 2 minutes more; after a uniform slurry was formed, perlite aggregate was added and the concrete was mixed for an additional 1½ minutes.
3. The vermiculite concretes were made by mixing water, air-entraining agent, and cement together for 1 to 2 minutes before adding the sand or lightweight aggregate (if used); the mixing operation was continued for 1 to 2 minutes before vermiculite aggregate was added, and then the concrete was mixed for an additional 1½ minutes.

Wet and oven-dry unit weights were determined in accordance with ASTM C138 and C495, respectively.

Curing and Conditioning

After concrete was placed in the forms, slab surfaces were struck off and finished with a wood float. Concrete was cured under damp burlap at 70 to 75 F for 5 days. Specimens were then conditioned in air maintained at 70 to 75 F and 30 to 40 percent relative humidity. Relative humidity at middepth of the slab was reduced to 76 percent or less before each specimen was mounted in a restraining frame for fire testing. Data on relationships between moisture content and relative humidity are given in Appendix A.

Thickness Measurement

Prior to fire tests, thicknesses of specimens (except C-30, P-29, and V-28) were measured at nine locations, including the thermocouple locations, and the average values are given in Table 3. Slab thicknesses were measured by placing the slab in a special frame, shown in Fig. 1, and inserting a rod 8.25 in. long through the frame at a measuring point on each side of the slab. The frame contains nine sets of measuring points having precise out-

TABLE 1. Data on Mixes

Mix no.*	Batch quantities, lb per cu yd: Cement, Type I	Preformed foam**	Perlite concrete aggregate	Vermiculite concrete aggregate	Sand	Water	Vinsol resin,† fl oz per cu yd	Average slump, in.	Average wet unit weight, pcf	Average oven-dry unit weight, pcf	Average compressive strength, psi
C-30	673††	54	–	–	–	371	–	10	41	30	325
C-58	721	26	–	–	765‡	292	–	10	67	58	460
C-78	636	17	–	–	1,355‡	264	–	9.5	84	78	820
C-100	606	9	–	–	1,935‡	312	–	8	106	100	2,190
P-29	424	–	216	–	–	454	115	6.5	41	29	205
P-58	572	–	135	–	655‡‡	377	30	7.5	64	58	610
P-74	504	–	115	–	1,190‡‡	369	17	6	81	74	920
V-28	424	–	–	162	–	756	111	7.5	50	28	235
V-54	556	–	–	155	620‡‡	606	63	7	72	54	485
V-70	620	–	–	80§	–	490	54	7	82	70	1,185
V-79	637	–	–	100	1,250‡‡	525	62	7	93	79	1,045

*The mix number indicates the concrete type (C for cellular, P for perlite, and V for vermiculite) as well as its oven-dry weight. For example, C-30 indicates cellular concrete with a unit weight of 30 pcf, oven-dry.
**Unit weight of foam was 2 pcf.
†12½ percent solution.
††Type III cement.
‡Masonry sand from South Beloit, Ill.
‡‡Concrete sand from Elgin, Ill.
§Plus lightweight aggregates (rotary-kiln-produced expanded shale from Ottawa, Ill.): medium, 680 lb per cu yd; fine, 357.

TABLE 2. Grading of Aggregates

Sieve size	Cumulative percent retained: Concrete sand*	Masonry sand**	Expanded shale†: Fine	Expanded shale†: Medium
3/8 in.	–	–	–	1
No. 4	2	–	0	56
No. 8	14	0	20	93
No. 16	33	1	51	100
No. 30	55	7	75	100
No. 50	85	76	90	100
No. 100	98	99	96	100
Fineness modulus	2.87	1.83	3.32	5.50

*Sand from Elgin, Ill.
**Sand from South Beloit, Ill.
†Rotary-kiln-produced expanded shale from Ottawa, Ill.

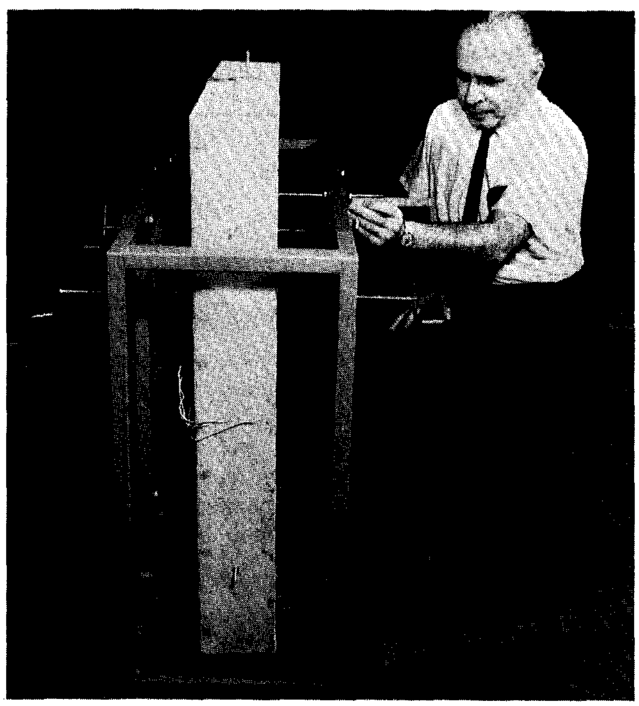


Fig. 1. Measuring the thickness of a 3x3-ft slab specimen.

TABLE 3. Data on Specimens and Fire Test Results

Mix no.*	Specimen thickness,** in.	Age at test, days	Middepth rel. humidity at test, percent	Fire endurance, hr:min	
				Test	Adjusted†
C-30	2.0	25	66	1:40	1:50
	3.5	26	64	4:31	4:57
	3.5	29	55	4:36	5:13
	5.0	30	70	7:38	7:57
	5.0	37	66	7:48	8:12
C-58	2.16	13	76	1:20	1:20
	3.67	25	76	3:20	3:19
	5.13	43	76	6:22	6:20
C-78	2.07	17	76	0:57	0:57
	3.71	26	76	2:21	2:20
	5.13	42	76	4:36	4:35
C-100	1.99	19	76	0:37	0:37
	3.56	45	75	1:39	1:39
	5.02	102	75	3:04	3:04
P-29	2.0	20	74	1:23	1:24
	3.5	40	76	3:54	3:52
	5.0	79	70	6:37	6:44
P-58	2.00	26	76	1:07	1:07
	3.53	41	75	3:12	3:12
	5.03	70	76	6:24	6:23
P-74	2.02	19	76	0:53	0:53
	3.49	46	75	2:19	2:19
	5.09	70	76	5:00	4:59
V-28	2.0	32	50	1:13	1:21
	3.5	53	59	3:22	3:36
	5.0	105	72	7:13	7:19
	5.0	79	75	7:33	7:33
V-54	2.14	28	74	1:14	1:14
	2.00	19	75	1:08	1:08
	3.65	46	74	3:19	3:20
	3.68	46	76	3:31	3:30
	5.16	90	74	6:40	6:42
	5.16	72	75	6:37	6:37
V-70	2.07	34	76	1:01	1:01
	3.53	103	74	2:35	2:35
	5.06	166	72	5:16	5:18
V-79	2.02	25	70	0:53	0:54
	3.59	54	76	2:33	2:33
	5.29	98	74	5:26	5:27

*The mix number indicates the concrete type as well as its oven-dry weight.
**Thicknesses of specimens (except C-30, P-29, and V-28, where nominal thicknesses are given) were measured to 0.01 in. as shown in Fig. 1.
†Adjusted for differences in moisture condition of specimens at time of test to values that would be appropriate for specimens with middepth relative humidity of 75 percent.

to-out dimensions of 16.50 in. The extension of the rod beyond the frame was measured with a machinist's scale to 0.01 in., and the sum of the rod extensions from both sides of the frame was the slab thickness at that point.

Fire Tests

Mounted in restraining frames, the specimens were subjected to standard fire exposure from beneath. The fire tests were conducted in the manner described in the first report,[1] including control of the furnace atmosphere temperature. The method is similar to that of ASTM E119, except for specimen size and loading.

DISCUSSION OF RESULTS

Unexposed Surface Temperatures

The average and maximum temperature rise of the unexposed surface during fire tests are shown in Fig. 2. Most of the curves have pronounced temperature "plateaus."[1] The fire endurance was determined by the duration of the fire test until the average temperature of the unexposed surface rose 250 F.

The graphs in Fig. 2 are useful in determining thicknesses of insulating concretes required to provide certain degrees of protection against fire. For example, suppose that perlite concrete having an oven-dry unit weight of about 50 pcf will be used in the construction of a vault for electronic equipment to withstand a 4-hr standard fire, and the interior surface of the vault must not reach 225 F at 4 hr. A temperature of 225 F is equivalent to a temperature rise during a fire test of about 150 F, since the initial temperature of the unexposed surface is generally about 70 to 75 F. It is assumed that surface temperatures measured under asbestos pads would be comparable to the temperatures of the interior surfaces of a closed vault.

The graph in Fig. 2 for perlite concrete with an oven-dry unit weight of 58 pcf (mix P-58) shows that a 5-in. slab will have a 150 F rise at about 5 hr 30 min, and a 3½-in. slab at about 2 hr 40 min. For 4 hr, the thickness would be about 4¼ in. of the 58-pcf mix. Concrete of 29 pcf would require about 4-in. thickness (see P-29 graph in Fig. 2) so that the safe and practical thickness with 50-pcf perlite concrete would be 4¼ in.

Fire endurance, as determined by the temperature rise of the unexposed sur-

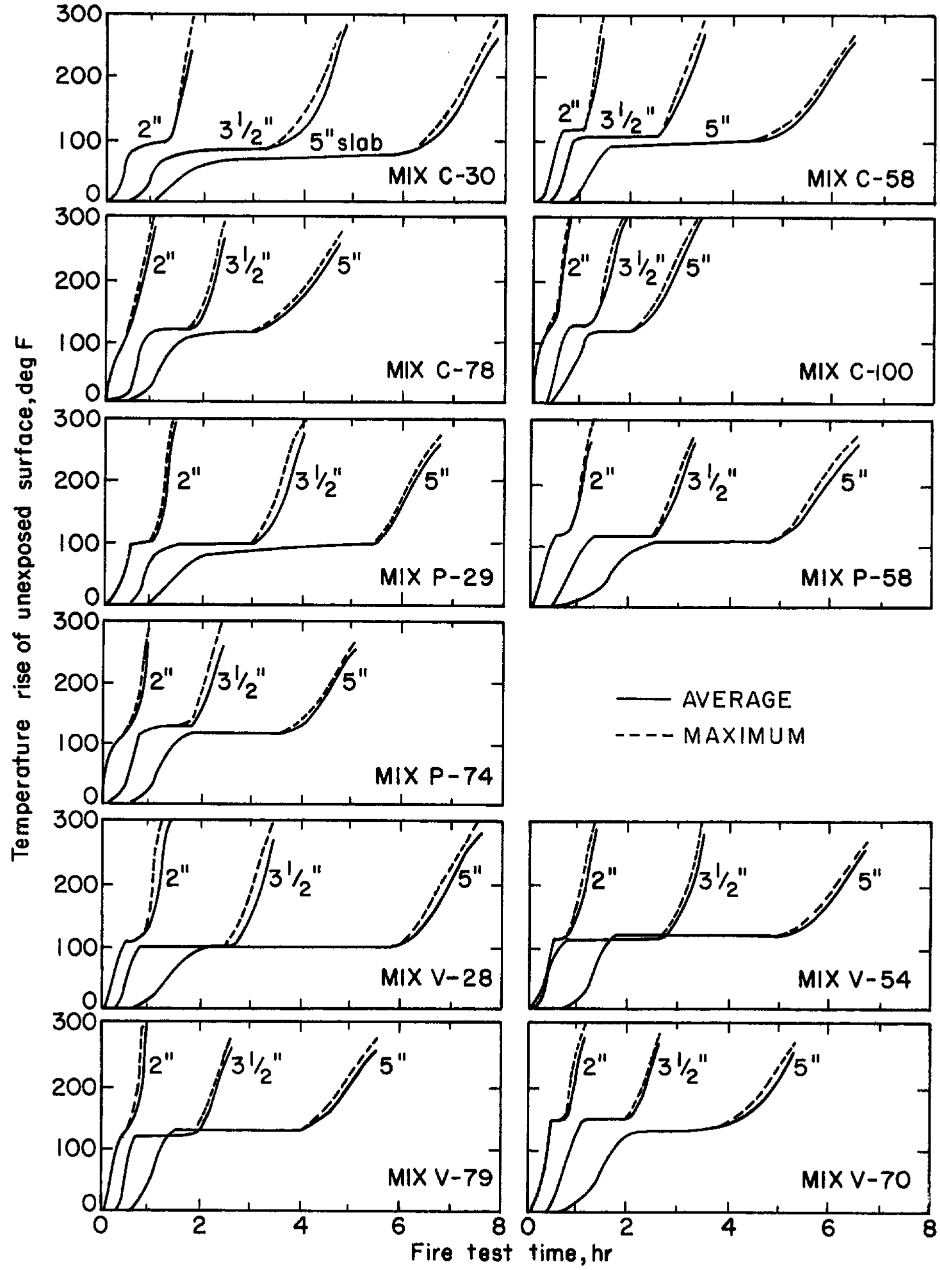


Fig. 2. Temperature rise of unexposed surface during fire tests.

humidity for each specimen are given in Table 3.

The adjusted fire endurances are shown as a function of slab thickness for each of the concrete mixes in Fig. 3, while Fig. 4 shows fire endurance as a function of oven-dry unit weight and slab thickness for the three types of concrete.

Few, if any, full-scale fire tests that are directly comparable to those included in this study have been conducted on slabs of insulating concrete. In 1953 the Vermiculite Institute sponsored an exploratory series of fire tests of spandrel walls of vermiculite concrete.[5] The vermiculite concrete was spray-applied to make 3x3-ft specimens with thicknesses of 2, 2½, 3, and 4 in. Mitchell[6] analyzed the results of those tests and concluded that thicknesses of 1.82, 2.57, 3.15, and 3.63 in. would be required for fire endurances of 1, 2, 3, and 4 hr for vermiculite concrete having an oven-dry unit weight of 47 pcf. In the present study, comparable thicknesses would be about 1.8, 2.6, 3.3, and 3.9 in., respectively. These values are reasonably conservative, even though the specimens were slabs rather than walls, the concrete was not spray-applied, and the specimens were conditioned differently prior to test.

A full-scale spandrel wall specimen was fire-tested in 1954.[7] The 4¼-in.-thick specimen was made of vermiculite concrete having an oven-dry density of 46.4 pcf. The fire endurance of 5 hr 44 min was somewhat longer than that estimated from Fig. 4. The relative humidity of the full-scale specimen was not monitored and it is possible that the moisture content of the wall was higher than that used in the present study.

face, is influenced by the moisture content of the specimen.[1,4] A higher moisture content results in a longer fire endurance based on heat transmission through the material. Harmathy[4] has suggested a method for adjusting the fire endurance determined from a specimen which has a moisture condition different than the "standard" condition, i.e. 75 percent relative humidity at middepth at time of test. A similar method that is under consideration for adoption as part of ASTM E119 was used in this study. Both the test and adjusted fire endurances as well as the middepth relative

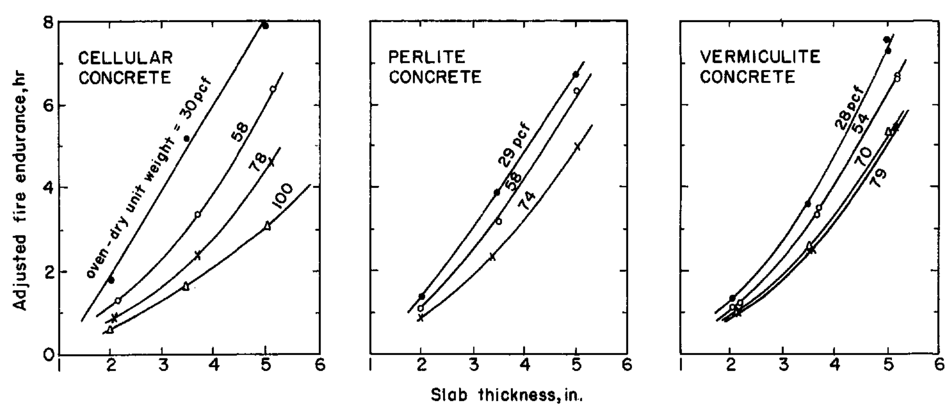


Fig. 3. Relationship between slab thickness and adjusted fire endurance for each of the concrete mixes.

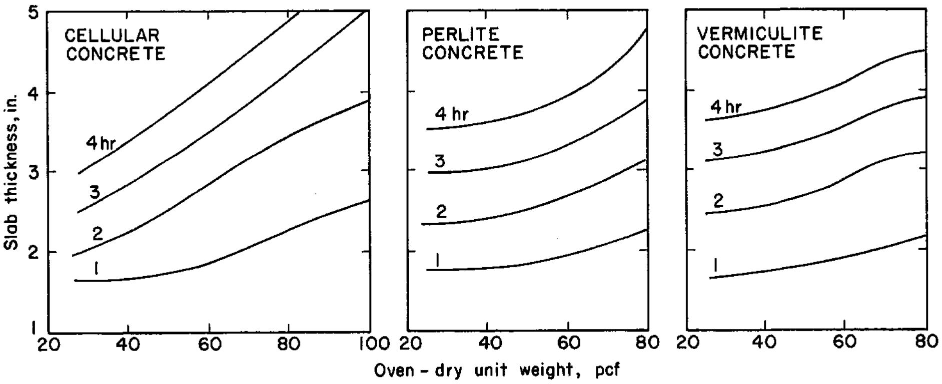


Fig. 4. Influence of unit weight and slab thickness on fire endurance of lightweight insulating concretes.

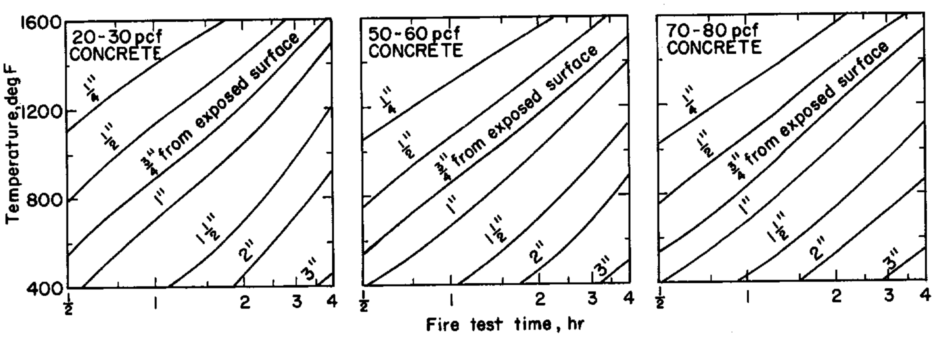


Fig. 5. Temperatures within insulating concrete slabs of different unit weights during fire tests.

NOTES: Chart (a) is a design chart from Reference 2 and Chart (b) is the same chart modified for 50-pcf cellular concrete according to the thicknesses given in Fig. 4 for 1, 2, 3, and 4 hr. Dashed lines in Chart (b) are tangent to solid lines at abscissa. These charts estimate that a 2-in. base slab of siliceous aggregate concrete with a 2-in. overlay of 30-pcf cellular concrete has fire endurance of almost 3 hr, but the same base slab with a 2-in. overlay of 50-pcf cellular concrete has fire endurance of about 2 hr 40 min.

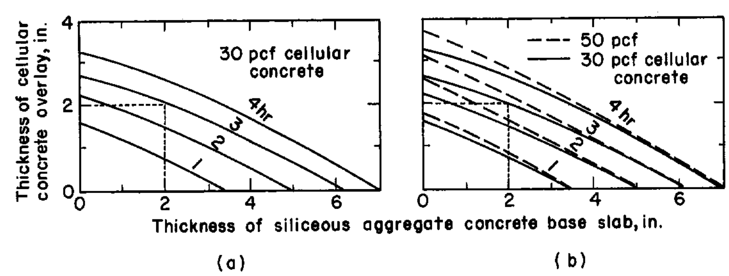


Fig. 6. Example of a design chart modified for a different overlay.

CONVERSION FACTORS—British to Metric Units of Measurement

Multiply	By	To obtain
Inches	2.54	Centimeters
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic yard	0.5933	Kilograms per cubic meter
Pounds per square inch	0.0703	Kilograms per square centimeter
Fluid ounces per cubic yard	0.0387	Liters per cubic meter

Temperatures Within Concrete Slabs

A typical plot of temperature distribution through concrete slabs of different unit weights during standard fire tests is shown in Fig. 5, and data for the three types of insulating concretes are shown in Appendix B. From the data, temperatures of embedded materials such as reinforcing steel can be estimated.

A previous study(1) showed that slab thickness has only a minor effect on the temperature at a given distance from the fire-exposed surface. In this study, the same conclusion was reached for insulating lightweight concretes.

Two-Course Floors and Roofs

Results of fire tests of two-course floors and roofs consisting of concrete base slabs with overlays of insulating concretes having oven-dry unit weights of about 30 pcf have been reported.(2) Even though no tests were conducted with overlays of heavier insulating concretes, their fire endurances can be estimated.

Suppose that the fire endurance is to be estimated for an assembly consisting of a 2-in. base slab of siliceous aggregate concrete with a 2-in. overlay of cellular concrete having an oven-dry unit weight of 50 pcf. Fig. 6(a) is a design chart(2) for estimating the fire endurance of siliceous aggregate concrete base slabs with cellular concrete overlays (30 pcf), and Fig. 6(b) is a modification, with dashed lines representing the 50-pcf cellular concrete overlays. The dashed lines are tangent to the solid lines at the abscissa and intercept the ordinate at the thicknesses obtained from Fig. 4: 1.75, 2.60, 3.10, and 3.70 in. for 1, 2, 3, and 4 hr, respectively. The fire endurance can be estimated by interpolating between the dashed lines. For this example, the fire endurance is estimated to be about 2 hr 40 min. Additional design charts are shown in Appendix C.

SUMMARY

Slabs made of cellular, perlite, and vermiculite concretes having oven-dry unit weights between 30 and 100 pcf were subjected to the ASTM standard fire. Data obtained included temperature of the unexposed surface and temperatures within the slabs.

The fire endurance, based on unexposed surface temperature rise, can be estimated for two-course floors or roofs made of these types of concretes combined with structural concrete base slabs.

An increase in unit weight resulted in a decrease in the fire endurance for each type of concrete.

REFERENCES

1. Abrams, M. S., and Gustaferro, A. H., "Fire Endurance of Concrete Slabs as Influenced by Thickness, Aggregate Type, and Moisture." *Journal of the PCA Research and Development Laboratories*, Vol. 10, No. 2, May 1968, pages 9-24. Also, Portland Cement Association Research Department Bulletin 223.
2. Abrams, M. S., and Gustaferro, A. H., "Fire Endurance of Two-Course Floors and Roofs." *Journal of the American Concrete Institute*, Feb. 1969; *Proceedings*, Vol. 66, No. 2, pages 92-102.
3. ACI Committee 523, "Guide for Low Density Precast Concrete Floor, Roof, and Wall Units." ACI *Journal*, July 1968; *Proceedings*, Vol. 65, No. 7, pages 507-512.
4. Harmathy, T. Z., "Effect of Moisture on Fire Endurance of Building Elements." *ASTM Symposium on Moisture in Relation to Fire Tests*, STP No. 385, American Society for Testing and Materials, Philadelphia, Pa., 1965, pages 74-95.
5. *Exploratory Fire-Endurance Tests on Vermiculite Concrete Spandrel Walls (2", 2½", 3" and 4" thick).* Vermiculite Institute, Chicago, Ill., Oct. 1954.
6. Mitchell, Nolan D., *Analysis of Fire Tests of Vermiculite Concrete Spandrel Walls.* Vermiculite Institute, 1954.
7. *4¼-In. Nonbearing Reinforced Vermiculite Concrete Spandrel Wall.* Report R-3653, Underwriters' Laboratories, Inc., Chicago, Aug. 18, 1954.

APPENDIX A. Moisture Content-Relative Humidity Relationships

Relationships between moisture content and relative humidity during the drying period following the 5 days of moist-curing are shown in Fig. A-1. These relationships were developed from measurements of 12x12x3½-in. specimens made of the same mixes used in the fire test specimens. Moisture specimens were cast in sheet metal side forms and fitted with humidity wells at middepth at the center. After 5 days of moist-curing under damp burlap, the specimens were dried on both 12x12-in. surfaces in an atmosphere of 70 to 75 F and 30 to 40 percent relative humidity. At periodic intervals, measurements were made of the relative humidity and weight of the specimens. After the specimens reached essentially constant weight in the conditioning atmosphere, they were dried to constant weight in an oven at 230 F.

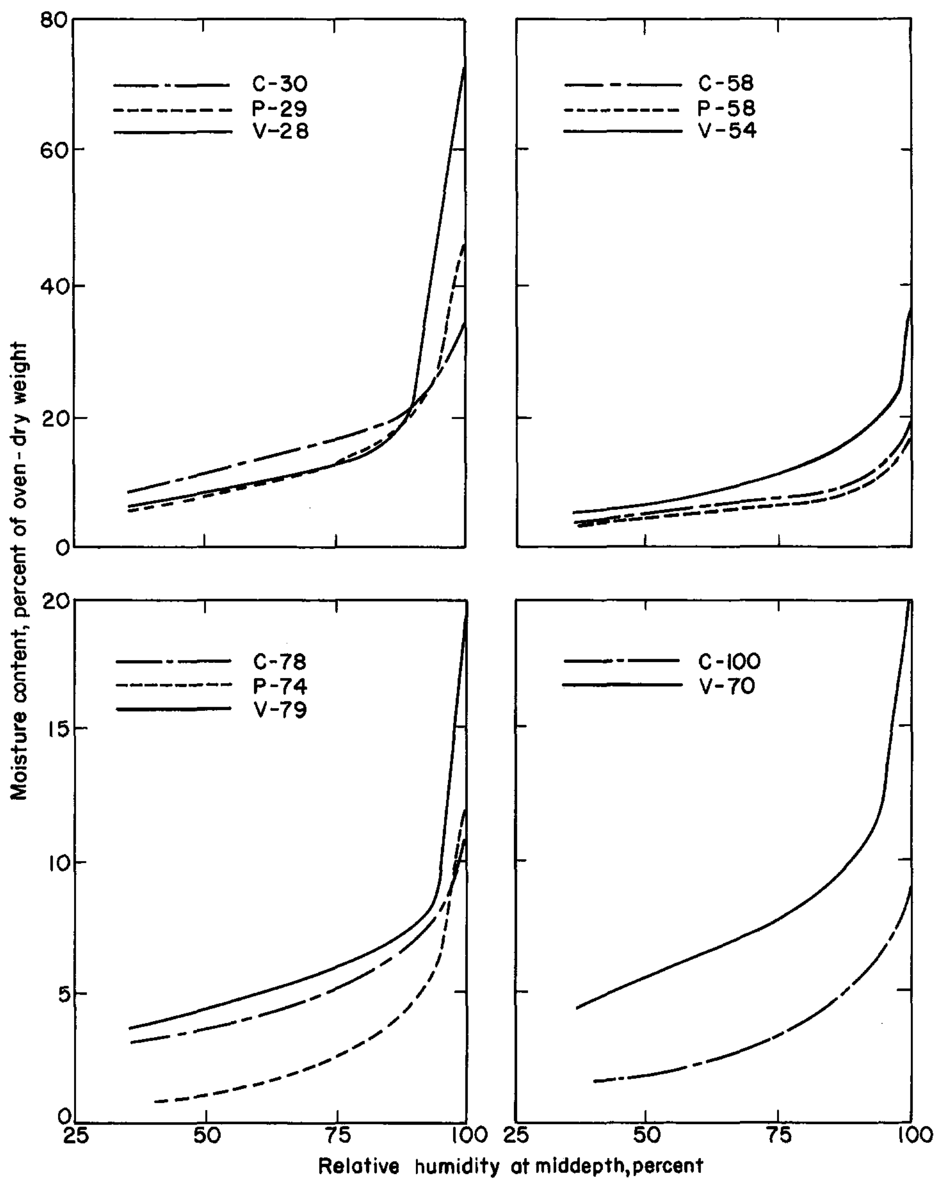


Fig. A-1. Moisture content-relative humidity relationships for 3½-in.-thick slabs of lightweight insulating concrete.

APPENDIX B. Temperature Distribution During Fire Tests

Data on temperature distribution within slabs of the three types of lightweight insulating concretes during fire tests for 1, 2, 3, and 4 hr are shown in Fig. B-1. Some estimated values for perlite concrete are included.

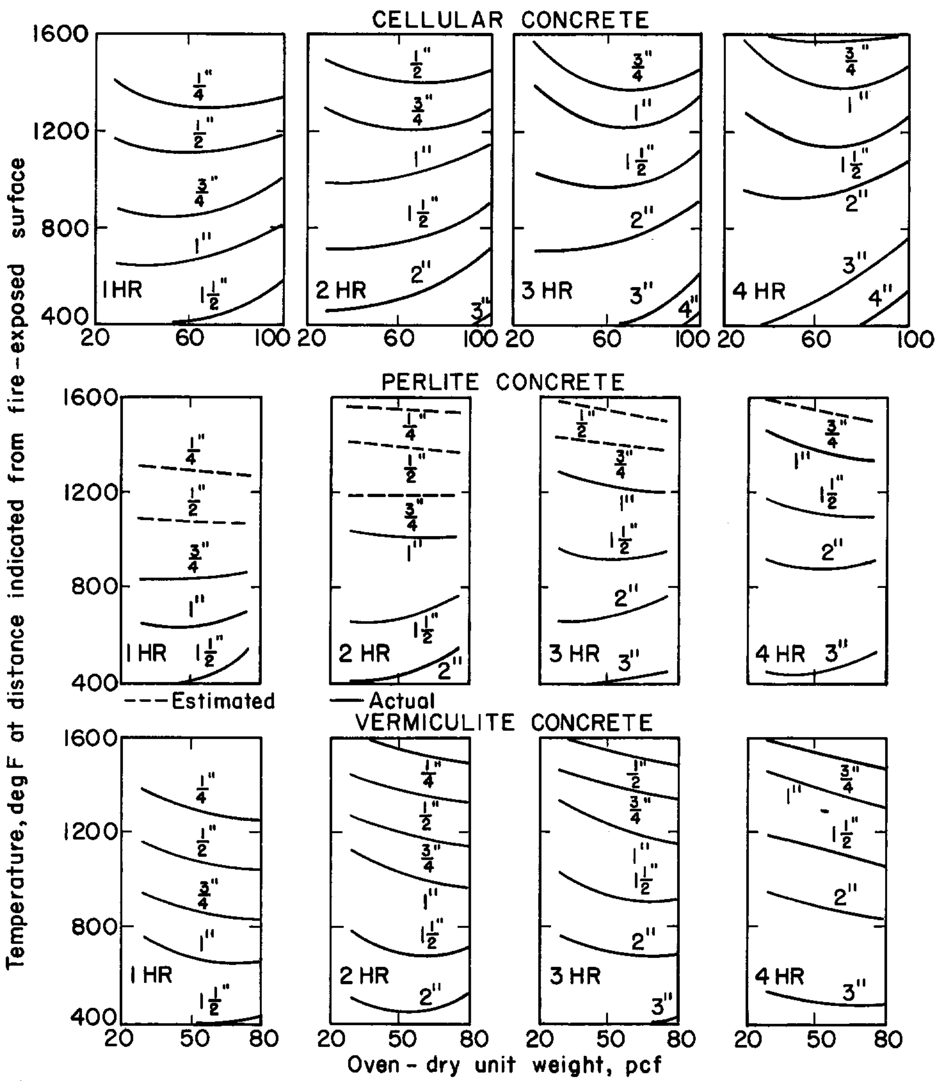


Fig. B-1. Temperatures within insulating concrete slabs during fire tests.

APPENDIX C. Design Charts for Two-Course Floors and Roofs

Charts for estimating thicknesses of two-course floors and roofs for various fire endurance periods are shown in Figs. C-1, C-2, and C-3. The base slabs consist of structural concretes made with carbonate, siliceous, and expanded shale lightweight aggregates, and the overlays consist of the three types of insulating concrete used in this study. Data on mixes and aggregate properties for the structural concretes are given in the first report.(1) The charts were constructed for three oven-dry unit weights (30, 50, and 70 pcf) of insulating concrete in the manner shown in Fig. 6.

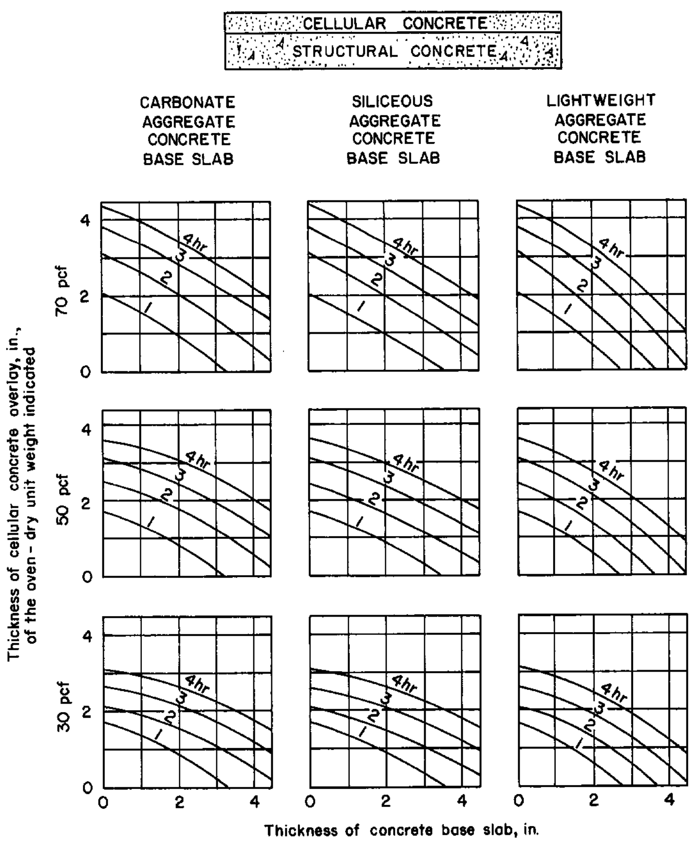


Fig. C-1. Fire endurance of slabs consisting of cellular concrete overlays on structural concrete base slabs.

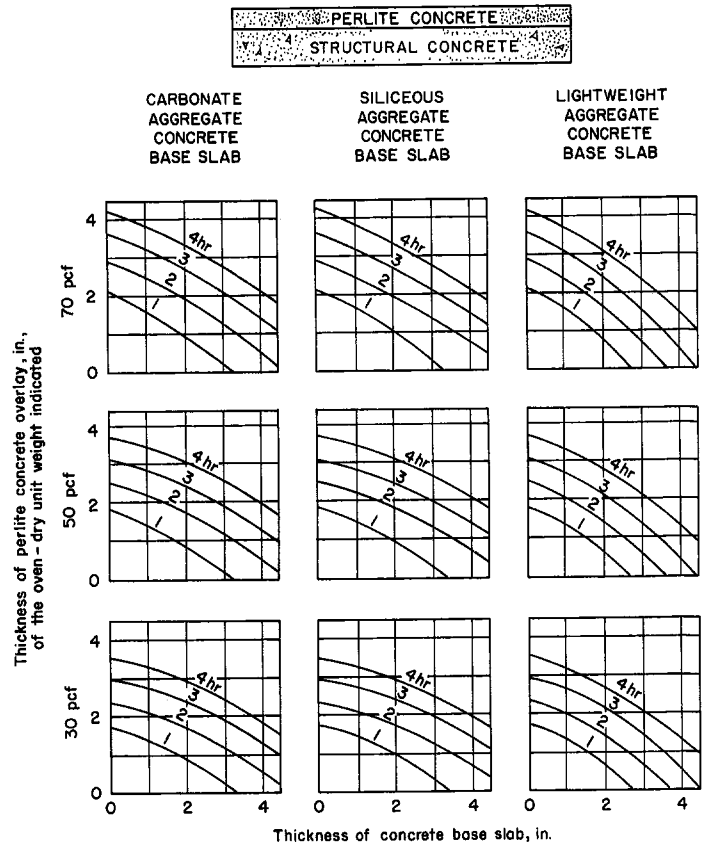


Fig. C-2. Fire endurance of slabs consisting of perlite concrete overlays on structural concrete base slabs.

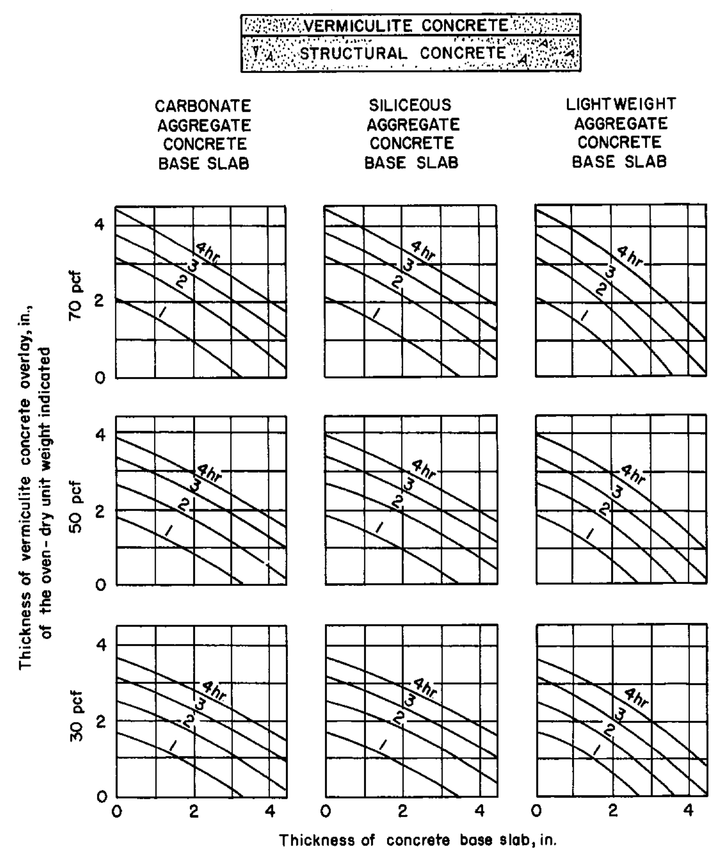


Fig. C-3. Fire endurance of slabs consisting of vermiculite concrete overlays on structural concrete base slabs.

KEY WORDS: cellular concretes, concrete slabs, fire resistance, fire tests, floors, insulating concretes, perlite, roofs, thermal insulation, vermiculite.

ABSTRACT: This report presents data on the fire resistance of concretes having oven-dry unit weights in the range of 30 to 100 pcf. Relationships between slab thickness and fire endurance, based on 250 F rise of the unexposed surface, are given for concretes with various unit weights. Data are also presented on temperature rise of the unexposed surface and temperature distribution through the slabs during fire tests. Design charts for estimating the fire endurance of two-course floors and roofs are discussed, and relationships between moisture content and relative humidity of fire test specimens are presented.

REFERENCE: Gustaferro, A. H.; Abrams, M. S.; and Litvin, Albert; *Fire Resistance of Lightweight Insulating Concretes* (RD004.01B), Portland Cement Association, 1970.

PORTLAND CEMENT ASSOCIATION

An organization of cement manufacturers to improve and extend the uses of portland cement and concrete through scientific research, engineering field work, and market development.

Old Orchard Road, Skokie, Illinois 60076

Printed in U.S.A.

RD004.01B