Portland Cement Association

Research & Development Information

PCA R&D Serial No. 2031

Thermal Properties of Commercially Available High-Strength Concretes

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Serial No. 2031

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REFERENCE: Van Geem, M. G., Gajda, J., and Dombrowski, K., **"Thermal Properties of Commercially Available High-Strength Concretes,"** *Cement, Concrete, and Aggregates,* CCAGDP, Vol. 19, No. 1, 1997, pp. 38–53.

ABSTRACT: This paper summarizes the thermal properties of commercially available high-strength concretes. Five concretes with anticipated compressive strengths in the range of 10 000 to 20 000 psi (69 to 138 MPa) were tested. *W/C* ratios ranged from 0.26 to 0.43; water-to-total cementitious material ratios ranged from 0.22 to 0.32. The concretes, containing either no mineral admixtures, silica fume only, or both fly ash and silica fume, were delivered by a ready-mix supplier for laboratory testing.

Tests covered by this paper include thermal conductivity, thermal diffusivity, specific heat, and drying rates. Thermal conductivity was measured using a guarded hot plate (ASTM C 177) at 85, 300, and 700°F (30, 150, and 370°C). Thermal conductivity was also measured using the hot-wire method (ASTM C 1113) at 70, 300, 570, 840, 1110, 1380, and 1830°F (25, 150, 300, 450, 600, 750, and 1000°C). Thermal diffusivity was measured, using the guarded hot plate apparatus, at 95, 250, and 500°F (35, 120, and 250°C). Thermal diffusivity was also measured using a dynamic radial heat flow method continuously from 210 to 1830°F (100 to 1000°C). Thermal properties at high temperatures differed depending on the method used. Specific heat was measured on saturated concrete at ambient temperatures. Rates of drying for initially moist cured specimens were determined by oven-drying thermal conductivity specimens at 150, 185, and 220°F (65, 85, and 105°C) prior to thermal testing. Mass loss was measured at temperatures up to 1740°F (950°C) at heating rates of 4, 36, and 90°F (2, 20, and 50°C) per minute.

KEYWORDS: drying rate, elevated temperatures, high-strength concrete, mass loss, portland cement, specific heat, thermal conductivity, thermal diffusivity, thermal properties

This report summarizes thermal properties of commercially available high-strength concretes. Other engineering properties of the same concretes have been previously reported (Burg 1994).

While there has been, and continues to be, significant work done on high-strength concrete, little work has been done on thermal properties of these concretes. Even less work has been done on thermal properties of high-strength concrete at elevated temperatures. These data are needed for modeling heat flow in high-strength concrete resulting from heat generated by cement hydration and for modeling heat transfer and moisture migration in high-strength concrete exposed to fire.

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For the reader's convenience, values in this report are presented in both inch-pound (IP) units and metric (SI) units. For some tables it was not possible to include both units of measure in one table. In those cases, two tables are presented. Tables with (IP) after the table number are inch-pound units while tables with (SI) after the table number are in metric units of measure. If no designation follows the table number, both units of measure are presented in the table. Both units of measure are included in each figure.

Scope

Five concretes with anticipated compressive strengths in the range of 10 000 to 20 000 psi (69 to 138 MPa) were tested. *W/C* ratios ranged from 0.26 to 0.43; water-to-total cementitious material ratios ranged from 0.22 to 0.32. The concretes, containing either no mineral admixtures, silica fume only, or both fly ash and silica fume, were delivered by a ready-mix supplier for laboratory testing.

Tests covered by this report include thermal conductivity, thermal diffusivity, specific heat, and drying rates. Thermal conductivity was measured using a guarded hot plate (ASTM C 177) at 85, 300, and 700°F (30, 150, and 370°C). Thermal conductivity was also measured using the hot-wire method (ASTM C 1113) at 70, 300, 570, 840, 1110, 1380, and 1830°F (25, 150, 300, 450, 600, 750, and 1000°C). Thermal diffusivity was measured, using the guarded hot plate apparatus, at 95, 250, and 500°F (35, 120, and 250°C). Thermal diffusivity was also measured using a dynamic radial heat flow method continuously from 210 to 1830°F (100 to 1000°C). Specific heat was measured on saturated concrete at ambient temperatures. Rates of drying for initially moist cured specimens were determined by oven-drying thermal conductivity specimens at 150, 185, and 220°F (65, 85, and 105°C) prior to thermal testing. Mass loss was measured at temperatures up to 1740°F (950°C) at heating rates of 4, 36, and 90°F (2, 20, and 50°C) per min.

Program Test Specimens

Prisms were cast from five high-strength concrete mixes. Mix proportions are shown in Table 1. A complete description of all mix designs, casting, curing, strength data, and other information was presented by Burg (1994). Specimens with nominal dimensions of 6 by 6 by 30 in. (150 by 150 by 760 mm) were cast into steel molds. Specimens were moist cured for 7 ± 1 month at 73.4 ± 3°F (23 ± 1.7°C) and 100% relative humidity. At various times during curing, the specimens were removed, tested in flexure,

TABLE 1a—*(IP) Concrete mixtures.*[a]

Parameter, units per cubic yard	Mix Number				
	1	2	3	4	5
Cement Type I, lb	950	800	820	950	800
Silica fume, lb[b]	...	40	80	150	125
Fly ash, lb	...	100	...	...	175
Coarse aggregate SSD, lb[c]	1800	1800	1800	1800	1800
Fine aggregate SSD, lb	1090	1110	1140	1000	1000
HRWR Type F, fl oz	300	300	290	520	425
HRWR Type G, fl oz	...	...	...	...	...
Retarder Type D, fl oz	29	27	25	38	39
Total Water, lb[d]	267	270	262	242	254
W/C ratio	0.281	0.338	0.320	0.255	0.318
Water:cementitious material ratio	0.281	0.287	0.291	0.220	0.231

[a]As reported by ready-mix supplier.
[b]Dry mass.
[c]Maximum aggregate size: $^1/_2$-in.
[d]Mass of total water in the mix including that in liquid admixtures.

TABLE 1b—*(SI) Concrete mixtures.*[a]

Parameter, units per cubic meter	Mix Number				
	1	2	3	4	5
Cement Type I, kg	564	475	487	564	475
Silica fume, kg[b]	...	24	47	89	74
Fly ash, kg	...	59	...	...	104
Coarse aggregate SSD, kg[c]	1068	1068	1068	1068	1068
Fine aggregate SSD, kg	647	659	676	593	593
HRWR Type F, liter	11.60	11.60	11.22	20.11	16.44
HRWR Type G, liter	...	...	...	...	...
Retarder Type D, liter	1.12	1.05	0.97	1.46	1.50
Total water, kg[d]	158	160	155	144	151
W/C ratio	0.281	0.338	0.320	0.255	0.318
Water:cementitious material ratio	0.281	0.287	0.291	0.220	0.231

[a]As reported by ready-mix supplier.
[b]Dry mass.
[c]Maximum aggregate size: 12.5 mm.
[d]Mass of total water in the mix including that in liquid admixtures.

and remaining portions returned to the moist storage condition. Prisms having nominal dimensions of 2 by 6 by 6 in. (50 by 150 by 150 mm) were then cut from the ends of the previously tested specimens using a water-cooled diamond-blade saw. The "best" prisms, possessing the least entrapped air voids and the smoothest surfaces, were then selected for thermal conductivity and thermal diffusivity testing. After the various drying schedules, prisms were placed in sealed plastic bags until thermal tests were conducted.

Thermal Conductivity

Thermal conductivity is the rate of heat flow through a body of unit thickness and unit area with a unit temperature difference between the two surfaces. Thermal conductivities were measured in accordance with ASTM C 177-85, Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus (ASTM 1993b). This method is a primary[3] test method for measuring thermal conductivity of building materials. Tests were performed on 2- by 6- by 6-in. (50- by 150- by 150-mm) prisms sliced from remaining ends of previously tested 6- by 6- by 30-in. (150- by 150- by 760-mm) beams. Two prisms were used for each thermal conductivity test.

[3]In this sense, *primary* means the apparatus does not need to be calibrated using results from another test method.

Test Procedure

Using a guarded hot plate, two similar (as close to identical as possible) samples of the material to be tested are placed on either side of a horizontal flat plate heater assembly consisting of a 5.88-in. (149.4-mm) square inner (main) heater surrounded by a separately controlled guard heater to form a 12-in. (300-mm) square assembly as shown in Fig. 1. The function of the guard heater is to eliminate lateral heat flow to or from the main heater thereby forcing all heat generated in the main heater to flow one-dimensionally through the two test samples. Liquid-cooled heat sinks (auxiliary or cold plates) are also placed in contact with the samples producing a uniform and constant temperature on the outside of each sample. The apparatus is surrounded by a container filled with vermiculite insulation. The vermiculite insulation serves

TABLE 2a—*(IP) Thermal conductivity specimen dimensions and unit weights.*

Mix No.	Specimen No.	Average Dimensions, in.			Specimen Mass, lb			Unit Weight, pcf		
		Thickness	Width	Length	Before Oven-Drying	Before Testing[a]	After Testing[b]	Before Oven-Drying	Before Testing[a]	After Testing[b]
1	7	1.998	6.00	5.96	6.42	6.06	5.87	155.3	146.6	142.0
1	8	1.995	6.00	5.96	6.44	6.09	5.90	156.0	147.5	142.9
2	7	1.996	6.00	5.94	6.39	6.00	5.56	155.2	145.7	134.9
2	2	1.994	6.00	5.94	6.37	5.99	5.55	154.9	145.6	134.9
3	7	1.993	6.00	5.95	6.43	6.05	5.86	156.3	147.0	142.4
3	1	1.993	6.00	5.95	6.38	6.07	5.91	155.1	147.5	143.6
4	7	2.014	6.00	5.91	6.55	6.23	n/a	158.6	150.8	n/a
4	8	1.997	6.00	5.91	6.35	6.04	5.94	155.0	147.5	145.0
5	2	1.989	6.00	6.03	6.38	6.30	5.99	156.0	151.2	143.8
5	5	1.992	6.00	6.11	6.37	6.32	5.99	156.0	149.7	141.9

[a]After oven-drying.
[b]After testing at approximate specimen mean temperatures of 85, 300, 700°F.

TABLE 2b—*(SI) Thermal conductivity specimen dimensions and unit weights.*

Mix No.	Specimen No.	Average Dimensions, mm.			Specimen Mass, g			Unit Weight, kg/m^3		
		Thickness	Width	Length	Before Oven-Drying	Before Testing[a]	After Testing[b]	Before Oven-Drying	Before Testing[a]	After Testing[b]
1	7	50.75	152.4	151.4	2918	2754	2668	2492	2352	2279
1	8	50.67	152.4	151.4	2927	2768	2682	2504	2368	2294
2	7	50.70	152.4	150.9	2904	2727	2525	2491	2339	2166
2	2	50.65	152.4	150.9	2895	2722	2521	2486	2337	2165
3	7	50.62	152.4	151.0	2922	2750	2663	2508	2360	2286
3	1	50.62	152.4	151.0	2900	2759	2686	2489	2368	2305
4	7	51.16	152.4	150.0	2977	2832	n/a	2545	2421	n/a
4	8	50.72	152.4	150.0	2886	2745	2700	2488	2367	2328
5	2	50.52	152.4	153.2	2900	2863	2722	2458	2427	2307
5	5	50.60	152.4	155.1	2895	2872	2722	2421	2402	2277

[a]After oven-drying.
[b]After testing at approximate specimen mean temperatures of 30, 150, 370°C.

a body. Values of thermal diffusivity are needed to model the time-dependent heat flow through concrete associated with its thermal mass. Thermal diffusivities were measured in accordance with a method used at the National Research Council, Canada (Stephanson 1987).

Test Specimens

Tests were performed on nominal 2- by 2- by 6-in. (50- by 50- by 150-mm) prisms sliced from the remaining ends of previously tested 6- by 6- by 30-in. (150- by 150- by 760-mm) beams. Two prisms were used for each thermal diffusivity test. Prisms were dried at selected temperatures and placed in sealed plastic bags for a period of 9 ± 1 months before testing.

Two "slots" with approximate dimensions of 0.08-in. (2-mm) wide by 0.08-in. (2-mm) deep were cut in one prism from each mix by a water-cooled diamond saw. The cuts were made from one edge along the length of the prism to its center to allow placement of two thermocouples to measure the center temperature during thermal diffusivity testing.

Prior to testing, concrete prisms were dried in a convection oven at 223 ± 4°F (106 ± 2°C) until the mass of the prisms varied by less than 0.1% over a 24-h period. This procedure removed most of the "free" unbound moisture from the concrete. Specimens are dried before testing to eliminate measurement errors due to moisture migration during testing.

Specimen dimensions and unit weights are presented in Table 4. The additional mass loss after testing is attributed to the complete removal of free moisture and the partial removal of chemically bound water from the concrete at temperatures up to approximately 700°F (370°C).

Test Procedure

Thermal diffusivity measurements were performed as described by Stephanson (1987) using the guarded hot-plate apparatus. The

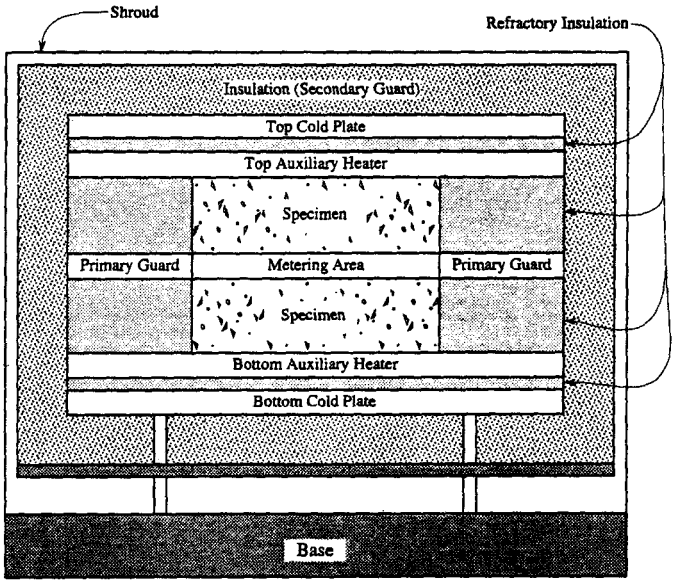


FIG. 1—*Guarded hot-plate apparatus (ASTM C 177).*

as a secondary guard. The guarded hot plate apparatus is located in a laboratory maintained at room temperature.

Specimen surface temperatures were measured with twenty 30-gage Type K (chromel-alumel) thermocouples. Five thermocouples were embedded in each heater surface and five were embedded in each auxiliary (cold) plate surface. Thermocouples consisted of bare wires within a 0.06-in. (1.5-mm) nominal diameter insulating round dual wire alumina sheathing. All thermocouples had nearly identical electrical resistances and were all from the same production lot to minimize variation and errors in temperature measurement. Measurements were made using a computer-based data acquisition and analysis system.

Prior to testing, the system accuracy was verified by testing two 1- by 12- by 12-in. (25- by 300- by 300-mm) specimens of National Institute of Standards and Technology (NIST) Reference Material 1451: Thermal Resistance—Fibrous Glass Blanket.

The rate of heat flow through the specimens is determined by measuring heat input into the heater plate. Thermal conductivity is calculated from three sets of data collected after equilibrium heat flow and temperatures are reached. Data sets are collected at 1-h time intervals.

Average thermal conductivity of the specimens is calculated from:

$$k = \frac{t}{\frac{\Delta T/2}{Q/A} - R_a} \tag{1}$$

where

t = specimen thickness, in. (m);
A = the metering surface area taken twice, ft^2 (m^2);
R = thermal resistance, h·ft^2·°F/Btu (m^2·K/W);
Q = power dissipation in the main heater, Btu/h (W);
A = the metering surface area taken twice, ft^2 (m^2);
ΔT = the total temperature difference across both specimens, °F (K); and
R_a = contact resistance factor, 0.073 h·ft^2·°F/Btu (0.0129 m^2·K/W).

A factor was applied to measured results to account for the contact resistance between the thermocouples in the apparatus and the specimen surfaces. This contact resistance factor, equal to 0.036 h·ft^2·°F/Btu (0.0064 m^2·K/W) for each of two sides, was determined from previous thermal conductivity tests on normal weight concrete specimens with embedded and surface-mounted thermocouples.

Test Specimens

The concrete had been moist-cured 47 ± 1 months at 73.4 ± 3°F (23 ± 1.7°C) and 100% relative humidity. Prior to testing, concrete prisms were dried in a convection oven at 223 ± 4°F (106 ± 2°C) until the mass of the prisms varied by less than 0.1% over a 24-h period. This procedure removed most of the "free" unbound moisture from the concrete. Specimens are dried before testing to eliminate measurement errors due to moisture migration during testing.

Specimen dimensions and unit weights are presented in Table 2. The additional mass loss after testing is attributed to the complete removal of free moisture and partial removal of chemically bound water from the concrete at temperatures up to approximately 700°F (370°C).

During testing, the specimens were surrounded by refractory ceramic fiber insulation to form a total specimen area of 12 by 12 in. (300 by 300-mm). The refractory ceramic fiber insulation was located only in the guard area of the sample. Preliminary tests on 2- by 12- by 12-in. (50- by 300- by 300-mm) concrete specimens showed large edge losses through the concrete in the guard area during testing at elevated temperatures. The refractory ceramic fiber insulation was used to minimize these losses.

Thermal Conductivity Test Results

Thermal conductivity test results are presented in Table 3. Results are averages for three consecutive data readings obtained after steady-state equilibrium was achieved. Test duration includes the time before steady-state equilibrium is reached. The average gradient is the temperature gradient across each specimen, averaged for the two specimens. Heat flux is the power to the main heater divided by the specimen metering area. Thermal conductivity was calculated using Eq 1.

Thermal conductivities of the high-strength concretes at ambient temperatures are similar to those for conventional strength normal weight concretes (Van Geem 1983). Thermal conductivity of concrete is primarily a function of the aggregate and paste densities but is also dependent on the aggregate type. Conventional strength concretes with oven-dry unit weights of 145 pcf (2320 kg/m^3) generally have thermal conductivities in the range of 12 to 18 Btu·in./h·ft^2·°F (1.7 to 2.6 W/m·K) at 75°F (24°C).

Figure 2 presents thermal conductivity test results as a function of temperature. For each concrete mix, thermal conductivity is relatively flat over the temperature range tested. Thermal conductivities of the high-strength concretes at high temperatures are similar to those for conventional strength normal weight concretes (Abrams 1980).

Results of thermal conductivity tests using the hot-wire method (ASTM C 1113) are presented in the Appendix.

Thermal Diffusivity

Thermal diffusivity is a physical property of a material that defines the time rate of change of temperature at any point within

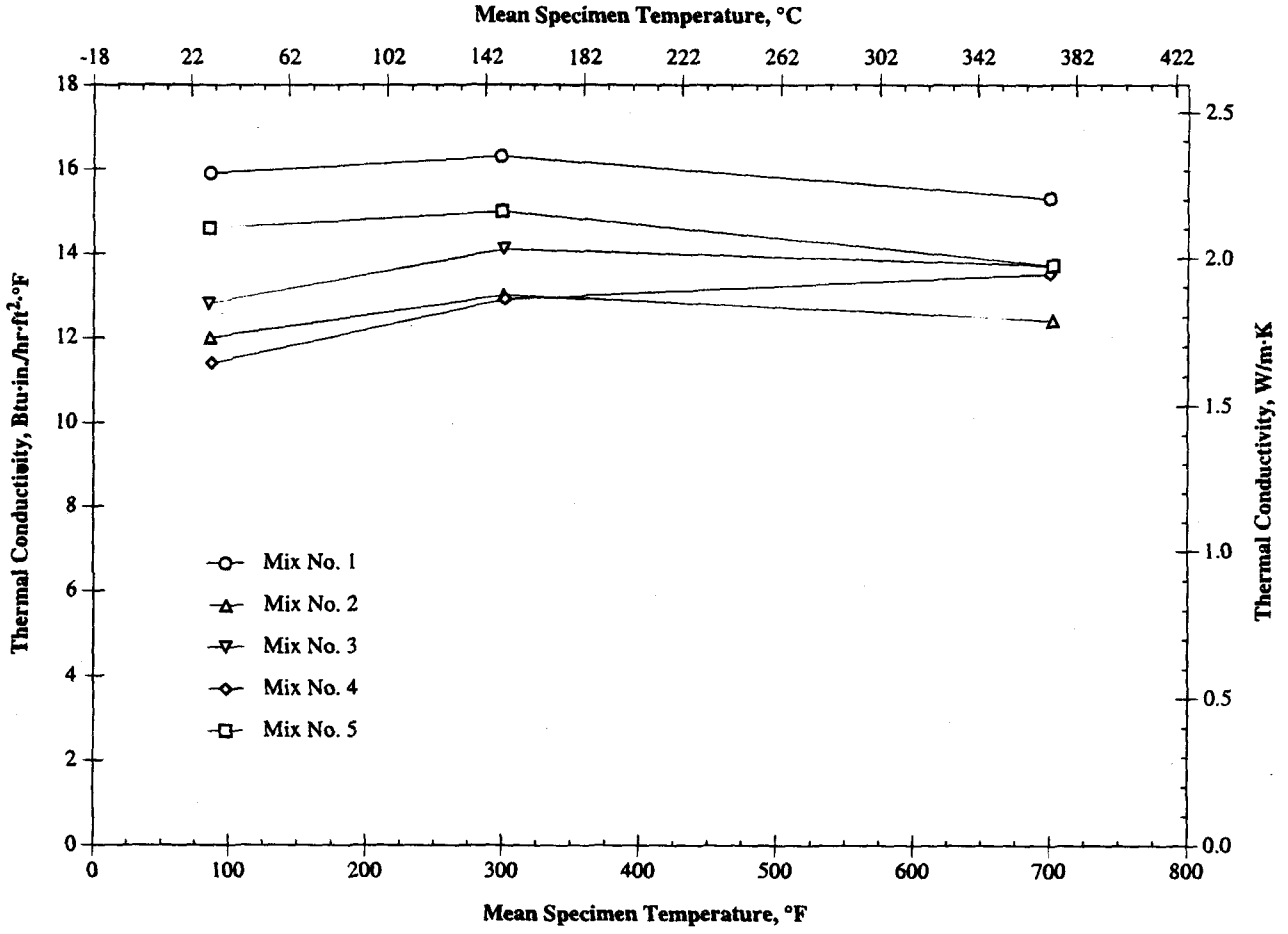


FIG. 2—*Thermal conductivity test results for high-strength concrete.*

TABLE 4a—*(IP) Thermal diffusivity specimen dimensions and unit weights.*

Mix No.	Specimen No.	Average Dimensions, in.			Specimen Mass, lb			Unit Weight, pcf		
		Thickness	Width	Length	Before Oven-Drying	Before Testing[a]	After Testing[b]	Before Oven-Drying	Before Testing[a]	After Testing[b]
1	1	1.944	6.00	6.08	6.37	6.03	5.34	155.3	147.0	130.3
1	3	1.977	6.00	6.06	6.24	5.91	5.26	149.9	142.0	126.3
2	1	1.976	6.00	6.04	6.31	5.92	5.18	152.3	143.0	125.2
2	8	1.991	6.00	6.06	6.37	5.99	5.23	152.2	143.0	124.8
3	5	1.989	6.00	6.04	6.39	5.99	5.42	153.1	143.5	130.0
3	8	1.980	6.00	6.09	6.39	6.01	5.42	152.7	143.5	129.4
4	1	1.988	6.00	5.91	6.34	6.03	5.26	155.6	147.9	129.1
4	2	1.959	6.00	5.99	6.31	6.01	5.21	154.8	147.7	127.9
5	7	1.994	6.00	6.01	6.35	6.01	5.32	156.0	144.5	128.0
5	8	1.978	6.00	5.96	6.31	5.95	5.27	156.0	145.3	128.9

[a]After oven-drying.
[b]After testing at maximum temperatures of approximately 1050°F.

TABLE 3a—*(IP) Thermal conductivity test results.*[a]

Mix No.	Test Date	Test Duration,[b] days	Temperature, °F: Hot Side Temperature	Cold Side Temperature	Average Gradient	Mean Specimen Temperature	Calculated Properties: Heat Flux, Btu/h·ft²	Thermal Conductivity,[c] Btu·in./h·ft²·°F
1	1/21/94	2	90	81	9	86	45	15.9
1	1/24/94	3	309	289	19	299	100	16.3
1	1/26/94	2	710	691	20	700	98	15.3
2	1/7/94	4	92	81	11	86	45	12.0
2	1/10/94	3	312	290	22	301	99	13.0
2	1/13/94	3	713	690	23	702	97	12.4
3	2/2/94	2	90	80	10	85	45	12.8
3	2/4/94	2	312	290	21	301	100	14.1
3	2/7/94	3	713	691	21	702	97	13.7
4	2/12/94	2	92	81	11	87	45	11.4
4	2/14/94	2	313	290	23	302	100	12.9
4	2/17/94	3	711	690	22	700	97	13.5
5	2/24/94	3	90	80	9	85	45	14.6
5	2/26/94	2	311	290	21	300	100	15.0
5	3/2/94	4	713	692	21	702	97	13.7

[a]Measured in accordance with ASTM C 177-85 using a guarded hot plate.
[b]Includes time before steady-state equilibrium is achieved.
[c]All specimens had nominal thicknesses of 2 in.

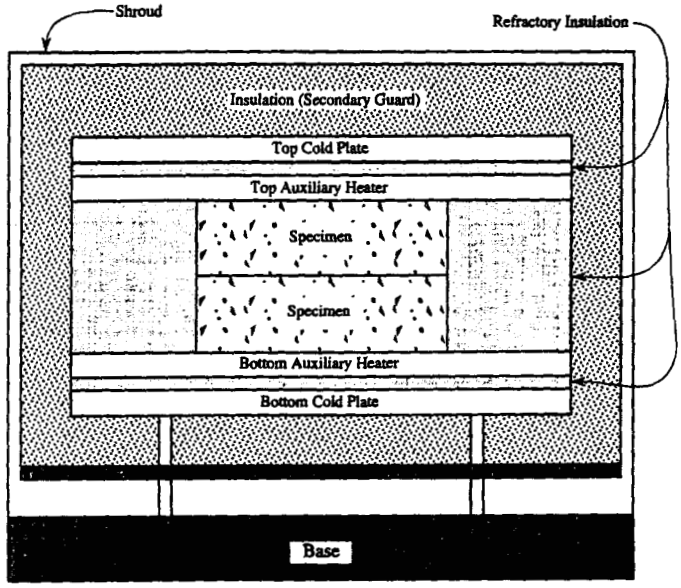
TABLE 3b—*(SI) thermal conductivity test results.*[a]

Mix No.	Test Date	Test Duration,[b] days	Temperature, °C: Hot Side Temperature	Cold Side Temperature	Average Gradient	Mean Specimen Temperature	Calculated Properties: Heat Flux, W/m²	Thermal Conductivity,[c] W/m·K
1	1/21/94	2	32	27	5	30	142	2.3
1	1/24/94	3	154	143	11	148	314	2.3
1	1/26/94	2	377	366	11	371	308	2.2
2	1/7/94	4	33	27	6	30	141	1.7
2	1/10/94	3	156	143	12	150	313	1.9
2	1/13/94	3	378	366	13	372	305	1.8
3	2/2/94	2	32	27	6	30	141	1.8
3	2/4/94	2	155	143	12	149	315	2.0
3	2/7/94	3	378	366	12	372	305	2.0
4	2/12/94	2	33	27	6	30	141	1.6
4	2/14/94	2	156	144	13	150	315	1.9
4	2/17/94	3	377	365	12	371	307	1.9
5	2/24/94	3	32	27	5	29	141	2.1
5	2/26/94	2	155	143	11	149	314	2.2
5	3/2/94	4	378	366	12	372	306	2.0

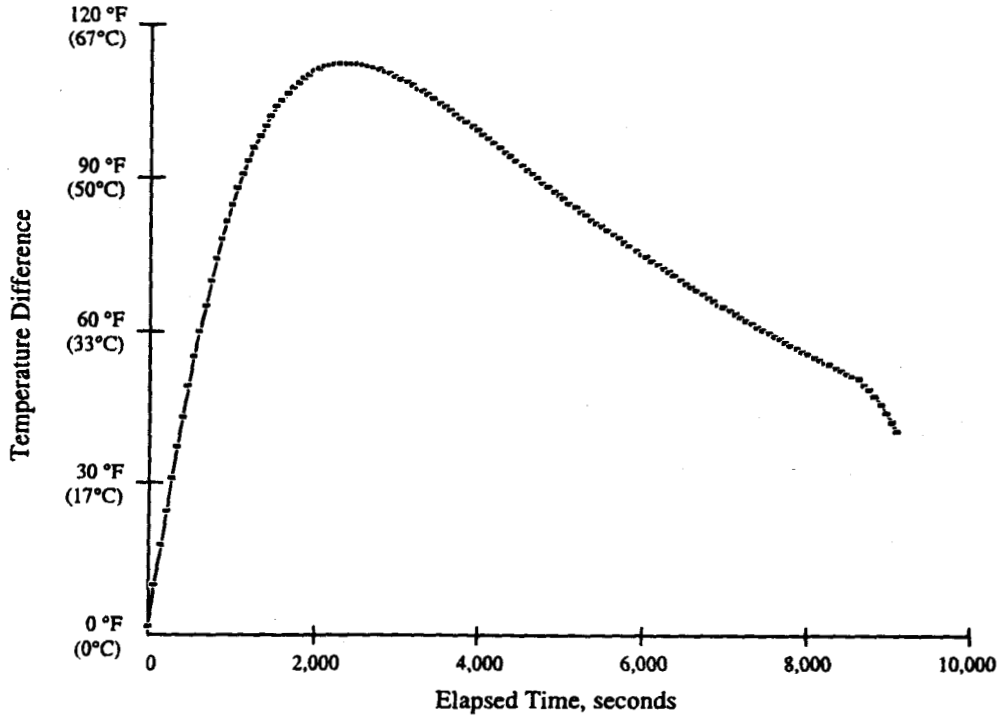
[a]Measured in accordance with ASTM C 177 using a guarded hot plate.
[b]Includes time before steady-state equilibrium is achieved.
[c]All specimens had nominal thicknesses of 50 mm.

main heater plate was removed and the auxiliary heater (cold) plates were used to apply a controlled decrease in temperature on the outside surface of the specimens. The thermal diff test apparatus (top), and typical data (bottom) shown in Figs. 3a & 3b is used to measure the temperature difference between the center and outer surfaces of a test specimen for a specific period of time. The thermal diffusivity of the test specimen is determined from the dimensions of the test specimen and the time versus temperature difference profile.

One variation was made from the procedure. The method called for a constant temperature decrease of the outer surfaces of the specimen. This was not practical on the test equipment used for this test. First, the specimen was allowed to reach equilibrium at the high end of the temperature range. The temperature of the specimen was then allowed to drop to a lower set point. Initially, the surface of the specimen cooled slowly, then maintained a uniform cooling rate, and then cooled slowly as the set point approached. At temperatures near room temperature, this method



(a) Cross-section in Elevation of Thermal Diffusivity Test Set-up



(b) Typical Time Versus Temperature Difference Profile for Thermal Diffusivity Test

FIG. 3—*Thermal diffusivity typical data.*

tory at 72 ± 5°F (22 ± 3°C) for 5 months, then stripped and air-dried at 73.4 ± 3°F (23 ± 1.7°C) and 50 ± 2% relative humidity for 44 months. Specimens were oven dried at 226 ± 1°F (108 ± 0.5°C) for 21 days after casting.

Specific heat values and associated concrete moisture contents are presented in Table 6. Specific heat values for normally dry conventional strength normal weight concrete generally range from 0.19 to 0.24 Btu/lb·°F (790 to 1000 J/kg·K) (Van Geem 1983). Values for the high-strength concrete are in the high end of this range and not significantly different from each other.

As well as being measured directly, specific heat can be theoretically calculated using the following relationship between thermal diffusivity, thermal conductivity, specific heat, and unit weight

$$\alpha = \frac{k}{\rho \cdot c} \tag{2}$$

where

α = thermal diffusivity, ft²/h (m²/s);
k = thermal conductivity, Btu/h·ft·°F (W/m·K);

TABLE 4b—*(SI) Thermal diffusivity specimen dimensions and unit weights.*

Mix No.	Specimen No.	Average Dimensions, mm			Specimen Mass, g			Unit Weight, kg/m^3		
		Thickness	Width	Length	Before Oven-Drying	Before Testing[a]	After Testing[b]	Before Oven-Drying	Before Testing[a]	After Testing[b]
1	1	49.37	152.4	154.3	2894	2739	2428	2492	2359	2091
1	3	50.22	152.4	153.9	2835	2685	2389	2407	2280	2028
2	1	50.18	152.4	153.3	2866	2691	2356	2444	2295	2009
2	8	50.56	152.4	153.9	2897	2723	2377	2443	2296	2004
3	5	50.52	152.4	153.4	2903	2721	2464	2458	2304	2086
3	8	50.28	152.4	154.7	2905	2730	2462	2451	2303	2077
4	1	50.50	152.4	150.0	2883	2741	2391	2497	2375	2071
4	2	49.76	152.4	152.1	2866	2733	2368	2485	2370	2053
5	7	50.65	152.4	152.6	2886	2732	2419	2451	2320	2054
5	8	50.24	152.4	151.3	2866	2702	2396	2473	2332	2068

[a]After oven-drying.
[b]After testing at maximum temperatures of approximately 565°C.

worked quite well. At elevated temperatures, the method was sufficient although the temperature ramp required to achieve a sufficiently long period of uniform cooling greatly increased as the desired test temperature increased.

Prior to testing, the slotted prism was placed onto the lower auxiliary heater (cold) plate of the guarded hot plate, slotted side facing upward. Two Type K thermocouples, of similar electrical resistance and the same production lot as the guarded hot-plate thermocouples, were placed into the slots. The companion prism was then placed on top of the slotted prism, and the upper auxiliary heater (cold) plate of the guarded hot plate was placed in contact with the prism assembly. Refractory ceramic fiber insulation was used to fill the guard area between the upper and lower plates of the guarded hot plate. An outer container was placed around the guarded hot plate and was filled with loose vermiculite insulation as a secondary guard.

The temperatures of the upper and lower auxiliary heater plates were then raised to the predetermined upper temperature of the test, and the temperature of the system was allowed to reach equilibrium. The temperature at the center of the two specimens was the average of two thermocouple readings. The temperatures of the plate surfaces were the average of three thermocouple readings. The exact time of the measurements and the temperatures of the thermocouples were recorded by the computer-based data acquisition system at 2-min intervals.

Immediately after the first set of five thermocouple measurements, the set point of the temperature controllers of the auxiliary plates was changed to the predetermined lower temperature of the test. Approximately 150 measurements of the average temperatures of the plates and center of the prism assembly were then made at 2-min intervals. Although the exact number of 2-min scans varied, at least 100 measurements were made before the plates reached their new set point. At the conclusion of the test, the time versus temperature difference profile of the assembly was analyzed.

Thermal Diffusivity Test Results

Table 5 presents the results of the thermal diffusivity testing. Each thermal diffusivity is associated with an "average" and "reported" temperature. The "average temperature" is the average of the initial (upper) and final (lower) temperatures of the temperature ramp. The "reported temperature" is the specimen mean temperature during the actual measurement of the thermal diffusivity. Measurements were made on each specimen at reported temperatures of 97 ± 2°F (36 ± 1°C), 255 ± 20°F (125 ± 10°C), and 475 ± 50°F (245 ± 30°C). Corresponding average temperatures were 99 ± 2°F (37 ± 1°C), 285 ± 5°F (140 ± 2°C), and 695 ± 15°F (365 ± 10°C), respectively. An effort was made to replicate mean temperatures from thermal conductivity testing, as the reported temperatures for the thermal diffusivity testing. However, differences occur due to the nature of the thermal diffusivity testing.

Thermal diffusivities of the high-strength concretes at ambient temperatures are similar to those for conventional strength normal weight concretes (Van Geem et al. 1983).

Figure 4 presents thermal diffusivity test results as a function of temperature. The thermal diffusivity of the high-strength concrete decreases with increasing temperature. The thermal diffusivity of conventional strength normal weight concrete at elevated temperatures also decreases with increasing temperature (Abrams 1980).

Results of thermal diffusivity tests using a radial method are presented in the Appendix.

Specific Heat

Specific heat was measured on saturated samples at ambient temperature in general accordance with U.S. Army Corps of Engineers method CRD-C 124-73, Method of Test for Specific Heat of Aggregates, Concrete, and Other Materials (Method of Mixtures). The measured material was crushed concrete passing the 1-in. (25.0-mm) sieve and retained on the No. 4 (4.75-mm) sieve. Concrete was obtained from 4- by 8-in. (102- by 203-mm) cylinders moist-cured 46 months at 73.4 ± 3°F (23 ± 1.7°C) and 100% relative humidity. The test is performed on saturated material alternately placed in water baths at 35 ± 1°F (2 ± 0.5°C) and 115 ± 1°F (46 ± 0.5°C).

Specific heat values for normally dry and oven-dry concrete are calculated from results on saturated material using a rule of mixtures approach (Whiting 1978). Oven-dry moisture contents were obtained from drying material from the specific heat test at 226 ± 1°F (108 ± 0.5°C). Normally dry moisture contents were obtained from 4- by 8-in. (102- by 203-mm) cylinders cast into sealed insulating polystyrene containers, and placed in a labora-

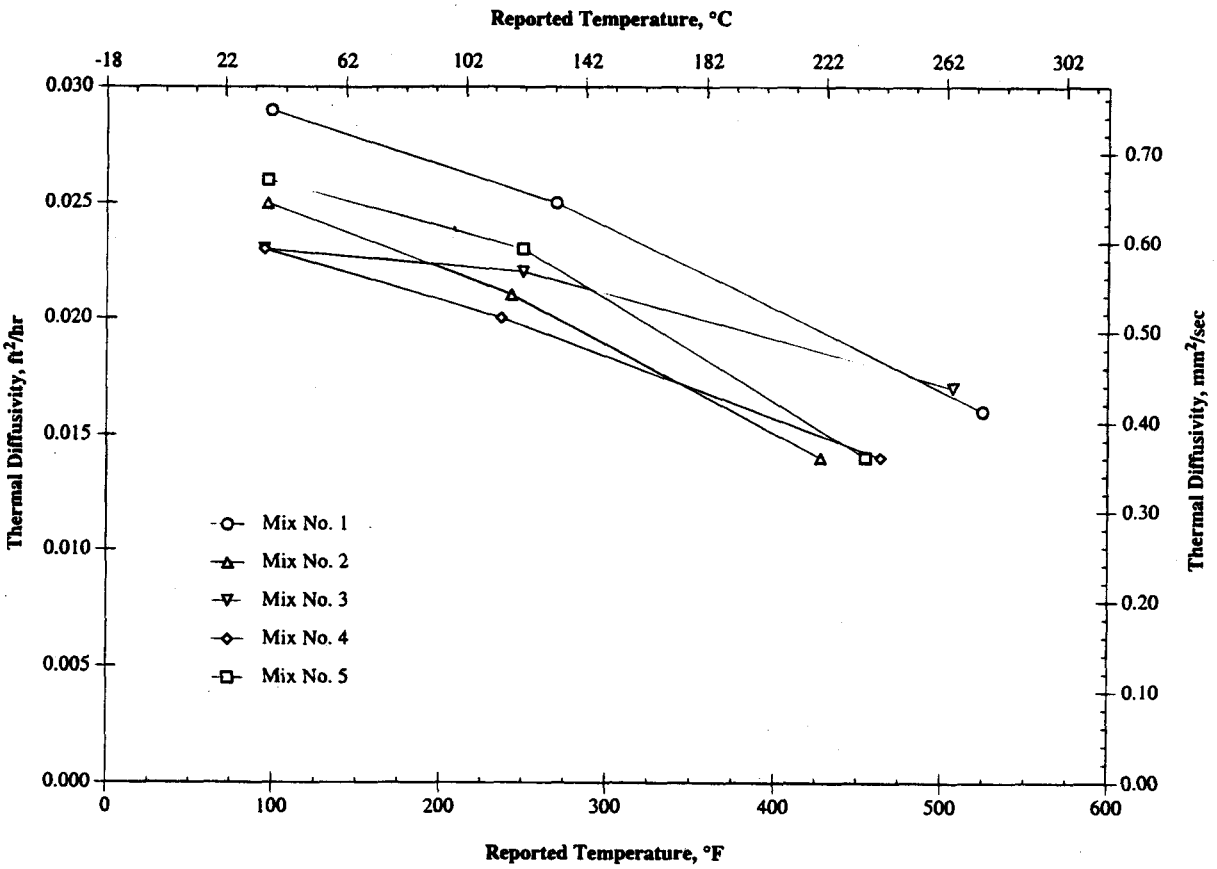


FIG. 4—*Thermal diffusivity test results for high-strength concrete.*

TABLE 6—*Specific heat of high-strength concrete at ambient temperature.*

Moisture Condition	Mix No.	Moisture Content, % Oven-Dry Mass	Specific Heat	
			Btu/lb · °F	J/kg·K
Saturated surface dry (SSD)	1	6.1	0.24	1000
	2	7.3	0.25	1050
	3	6.8	0.25	1050
	4	6.1	0.25	1050
	5	6.4	0.24	1000
Normally dry	1	3.4	0.22	920
	2	4.4	0.23	960
	3	4.9	0.24	1000
	4	4.2	0.23	960
	5	4.8	0.23	960
Oven-dry	1	0	0.20	840
	2	0	0.19	800
	3	0	0.20	840
	4	0	0.20	840
	5	0	0.19	800

TABLE 7—*Mass change of high-strength concrete at elevated temperatures with a heating rate of 3.6°F (2°C) per min.*[a]

Elapsed Minutes[b]	Temperature		Percent Mass Loss	
	°F	°C	Mix 1	Mix 5
0.0	61	16	0.00	0.00
24.4	158	70	0.22	0.42
52.2	257	125	1.05	1.69
83.5	356	180	1.95	2.71
111.4	450	232	2.46	3.28
139.2	550	288	2.82	3.62
170.5	644	340	3.19	3.97
198.4	752	400	3.56	4.29
229.7	856	458	4.09	4.61
261.0	957	514	4.51	4.88
292.4	1063	573	4.64	5.44
320.2	1159	626	4.93	6.23
348.1	1251	677	5.97	7.76
375.9	1348	731	9.17	12.08
407.2	1452	789	16.60	20.16
438.5	1564	851	26.34	31.84
462.9	1647	897	31.77	32.55
487.3	1731	944	31.90	32.61

[a]Mass loss as measured by thermogravametric analysis (TGA) in general accordance with ASTM C 114-92, Section 16.

[b]Data were collected at 3.5-min intervals. All data are not presented.

TABLE 5a—*(IP) Thermal diffusivity test results for high-strength concrete.*[a]

Mix No.	Temperature, °F				Thermal Diffusivity, ft²/h
	Initial[b]	Final[b]	Average[c]	Reported[d]	
1	111	84	98	99	0.029
1	349	221	285	270	0.025
1	1020	385	703	525	0.016
2	115	82	99	97	0.025
2	351	212	282	243	0.021
2	1022	342	682	428	0.014
3	113	88	101	95	0.023
3	351	223	287	250	0.022
3	1017	394	706	507	0.017
4	115	84	100	95	0.023
4	354	207	281	237	0.020
4	1018	383	701	464	0.014
5	115	86	101	97	0.026
5	351	212	282	250	0.023
5	1027	376	702	455	0.014

[a]Thermal diffusivity determined by a method described by Stephanson (1987).
[b]Initial and final temperatures of the temperature ramp determined by averaging the measured temperature of the top and bottom horizontal surfaces of the specimen.
[c]The average of the initial and final temperatures.
[d]Specimen mean temperature during the actual measurement of thermal diffusivity.

TABLE 5b—*(SI) Thermal diffusivity test results for high-strength concrete.*[a]

Mix No.	Temperature, °C				Thermal Diffusivity, mm²/s
	Initial[b]	Final[b]	Average[c]	Reported[d]	
1	44	29	36	37	0.74
1	176	105	141	132	0.65
1	549	196	373	274	0.41
2	46	28	37	36	0.65
2	177	100	139	117	0.55
2	550	170	360	222	0.35
3	45	31	38	35	0.59
3	177	106	142	121	0.56
3	547	201	374	264	0.44
4	46	29	38	35	0.58
4	179	97	138	114	0.51
4	548	195	371	240	0.37
5	46	30	38	36	0.66
5	177	100	139	121	0.60
5	553	191	372	235	0.37

[a]Thermal diffusivity determined by a method described by Stephanson (1987).
[b]Initial and final temperatures of the temperature ramp determined by averaging the measured temperature of the top and bottom horizontal surfaces of the specimen.
[c]The average of the initial and final temperatures.
[d]Specimen mean temperature during the actual measurement of thermal diffusivity.

ρ = unit weight, lb/ft³ (kg/m³); and
c = specific heat, Btu/lb·°F (J/kg·K).

If any three of the values of conductivity, specific heat, unit weight, or diffusivity are known, the fourth can be calculated. Test methods are available to measure each of the four properties. When using the equation, measured values should be from specimens at the same moisture content because thermal properties vary considerably depending on moisture content.

An attempt was made to calculate specific heat at elevated temperatures using measured thermal conductivity, thermal diffusivity, and unit weight for oven-dry conditions. Resulting values were not consistent with literature for normal weight concrete indicating that the test methods are not compatible for calculating specific heat. This is a recurring problem in the thermal measurements field and requires more research to investigate possible causes.

Mass Loss

Mass loss was measured in general accordance with procedures outlined in ASTM C 114-92, Methods for Chemical Analysis of Hydraulic Cement, Section 16—Loss on Ignition (ASTM 1993a). Mass loss was measured on oven-dried crushed concrete passing the No. 50 (300-μm) sieve. Concrete was obtained from 4- by 8-in. (102- by 203-mm) cylinders moist-cured 50 months at 73.4 ± 3°F (23 ± 1.7°C) and 100% relative humidity. Sample size of the crushed concrete prior to testing ranged from 2.9 to 5.1 g. Mass loss was measured over time at increasing temperatures up to 1740°F (950°C) at heating rates of 4, 35, and 90°F (2, 20, and 50°C) per min.

Figures 5, 6, and 7 and Tables 7, 8, and 9 present mass loss as a function of temperature and heating rate. As evident in Figs. 5 through 7, mass loss, at a particular temperature, varies in accordance with the heating rate because physio-chemical reactions at elevated temperatures are not instantaneous reactions. In general, a slower heating rate allows for more complete physio-chemical reactions; in this case, increased mass loss at a particular temperature. Mass loss at a heating rate of 4°F (2°C) per min was significantly increased compared to that at a higher heating rate of 36°F (20°C) or 90°F (50°C) per min.

It is assumed that the mass loss in the oven-dried high-strength concrete is due only to the release of chemically bound water and carbon dioxide (CO_2). In general, a rapid increase in the release of chemically combined water occurs at temperatures near 925°F (500°C). Carbon dioxide is generally released from dolomitic limestone aggregates in the temperature range of 1300 to 1650°F (700 to 900°C). The release of CO_2 from dolomite occurs near 1300°F (700°C), and the release from calcite ($CaCO_3$) occurs near 1650°F (900°C). The mass loss of the high-strength concretes are similar to values for conventional strength concretes with calcareous aggregates (Bazant et al. 1982).

Tables 2 and 4 present the mass of guarded hot plate and thermal diffusivity specimens before and after testing at elevated temperatures. These mass losses are different from those presented in Figs. 5, 6, and 7 because of the difference in specimen size, exposure temperature, and the extended time at elevated temperatures.

Rates of Drying

Moisture content and rate of moisture loss were measured at selected temperatures. Tests were performed on 2- by 6- by 6-in.

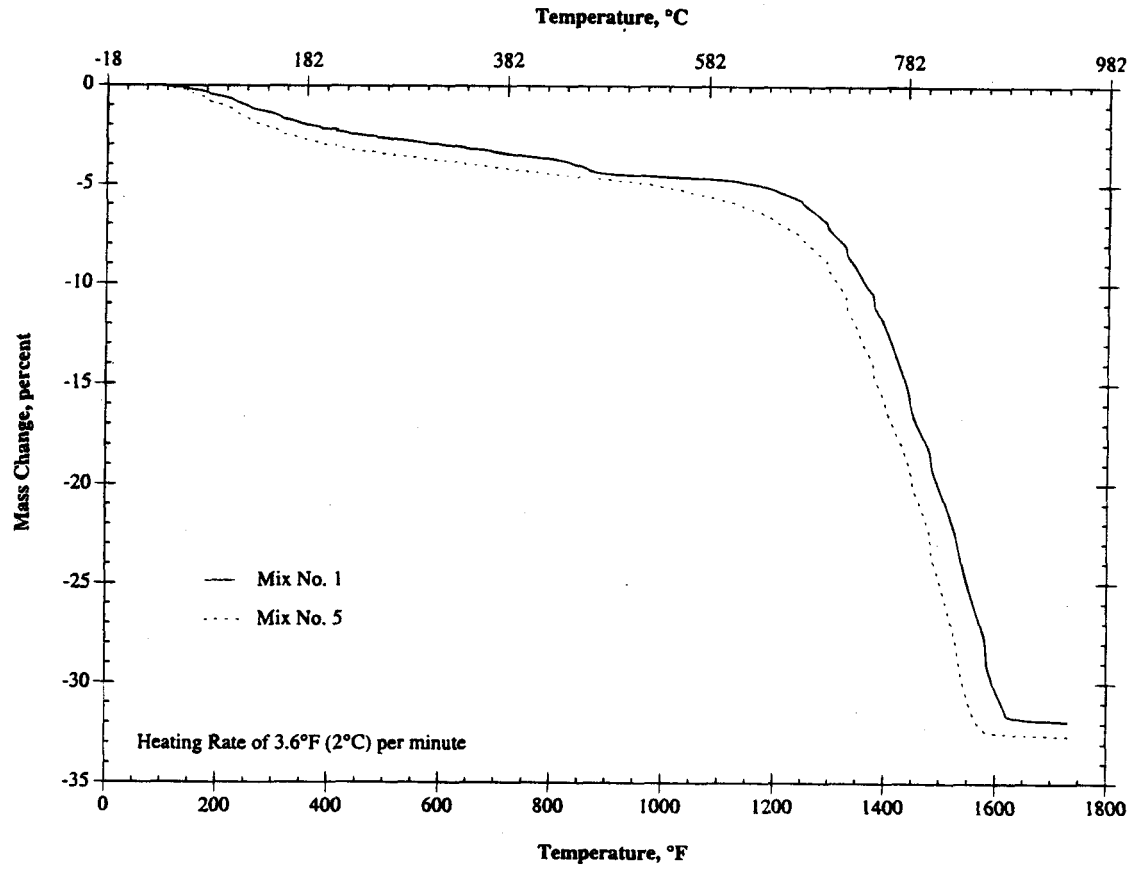


FIG. 5—*Mass loss of high-strength concrete at elevated temperatures.*

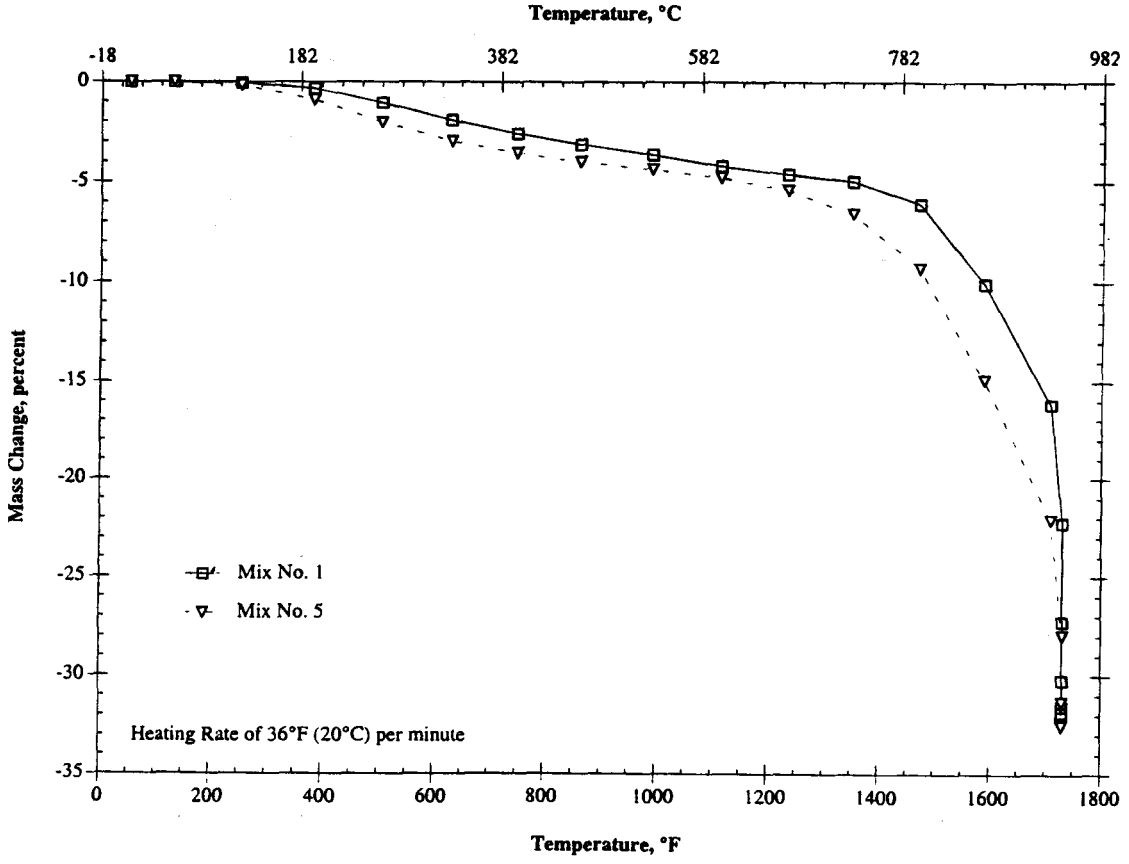


FIG. 6—*Mass loss of high-strength concrete at elevated temperatures.*

TABLE 8—*Mass change of high-strength concrete at elevated temperatures with a heating rate of 36°F (20°C) per min.*[a]

Elapsed Minutes	Temperature °F	Temperature °C	Percent Mass Loss Mix 1	Percent Mass Loss Mix 5
0.0	52	11	0.00	0.00
3.3	131	55	0.01	0.00
6.8	252	122	0.05	0.18
10.3	383	195	0.34	0.91
13.8	504	262	1.06	2.05
17.2	630	332	1.93	2.98
20.7	748	398	2.61	3.57
24.2	862	461	3.14	4.00
27.7	991	533	3.64	4.37
31.2	1114	601	4.20	4.77
34.6	1234	668	4.61	5.40
38.1	1351	733	4.94	6.57
41.6	1472	800	6.07	9.29
45.1	1589	865	10.07	14.91
48.6	1710	932	16.16	22.09
52.0	1731	944	22.23	27.96
55.5	1731	944	27.25	31.32
59.0	1731	944	30.21	32.42
62.5	1731	944	31.53	32.53

[a]Mass loss as measured by thermogravametric analysis (TGA) in general accordance with ASTM C 114-92, Section 16.

TABLE 9—*Mass change of high-strength concrete at elevated temperatures with a heating rate of 90°F (50°C) per min.*[a]

Elapsed Minutes	Temperature °F	Temperature °C	Percent Mass Loss Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
0.0	77	25	0.00	0.00	0.00	0.00	0.00
3.5	410	210	0.03	0.04	0.13	0.34	0.39
7.0	862	461	0.81	0.91	1.20	1.72	1.69
10.5	1189	643	2.54	2.51	2.67	3.30	3.29
13.9	1461	794	4.31	4.47	5.80	7.99	8.16
17.4	1693	923	10.85	11.36	15.19	18.05	17.17
20.9	1731	944	21.14	20.79	26.13	27.23	24.94
24.4	1731	944	27.92	26.43	30.92	30.43	28.63
27.9	1731	944	30.65	28.97	31.72	30.59	29.50
31.3	1731	944	31.10	29.59	31.75	30.60	29.53
34.8	1731	944	31.14	29.63	31.79	30.60	29.55
38.3	1731	944	31.14	29.64	31.79	30.59	29.54

[a]Mass loss as measured by thermogravametric analysis (TGA) in general accordance with ASTM C 114-92, Section 16.

(50- by 150- by 150-mm) prisms sliced from remaining ends of previously tested 6- by 6- by 30-in. (150- by 150- by 760-mm) beams. Prisms were stored at 73.4°F (22.8 ± 1°C) and 100% relative humidity for 47 ± 1 months prior to testing. One prism from each mix design was used for each test.

Concrete prisms were dried in a convection drying oven until the mass of the prism varied by less than 0.1% over a 24-h period. Specimens were subjected to one of four drying schedules: (1) 84 days at 150 ± 4°F (65 ± 2°C), (2) 20 to 23 days at 185 ± 4°F (85 ± 2°C), (3) 7 to 8 days at 220 ± 4°F (105 ± 2°C), and (4) 18 to 23 days at 220 ± 4°F (105 ± 2°C). Figures 6, 7, 8, and 9 present moisture loss as a percent of the final mass measurement. Lower drying temperatures caused the high-strength concrete to dry at slower rates. The slightly positive slopes of the curves in Figs. 8, 9, and 10 indicate that the concrete was still drying and had not reached equilibrium at the end of the test period even though unit weights varied by less than 0.1% over a 24-h period at the end of the test. For high-strength concretes, the procedure to dry until the mass changes by less than 0.1% over a 24-h period does not necessarily result in a specimen at an equilibrium unit weight. Equilibrium unit weights were reached only when specimens were dried at 220 ± 4°F (105 ± 2°C) for 18 to 23 days as shown in Fig. 11. High-strength concretes appear to require a longer drying period due to their decreased permeability.

Final moisture losses are summarized in Table 10. When the moisture loss of the concretes from the different mix designs are compared at the same drying temperatures, moisture loss appears to be related to the initial water content. Figures 8, 9, 10, and 11 and Table 10, show that concrete from Mixes 1 and 2 generally had greater moisture loss and greater initial water content than concrete from Mixes 4 and 5. Concrete from Mix 3 follows this trend when dried at 220 ± 4°F (105 ± 2°C) for 18 to 23 days as shown in Fig. 11.

During oven drying of the concrete prisms, black spots were noted on the sawed surfaces of the concrete. Typically, these spots were small, less than 0.2 in. (5 mm) diameter, either on or in close proximity to a piece of aggregate, and appeared to be oily. Petrographic analysis revealed that the black substance was residue from globules of bitumen that liquified and burned off (releasing light hydrocarbons and carbon dioxide) during heating. The bitumen was released by the dolomitic limestone aggregate. This is common in various sedimentary aggregates containing hydrocarbons.

Conclusions

This paper summarizes test results on the thermal properties of five commercially available high-strength concretes. These test results provide required information for modeling heat flow in high-strength concrete resulting from heat generated by cement hydration, and for modeling heat transfer and moisture migration in high-strength concrete exposed to fire.

The following conclusions are presented.

1. Values of thermal conductivity of the high-strength concretes measured at CTL using a guarded hot plate (ASTM C 177) are similar to those for conventional strength normal weight concretes. Measured values range from 12 to 18 Btu·in./h·ft²·°F (1.7 to 2.6 W/m·K) and are relatively constant over the temperature range of 85 to 700°F (30 to 370°C).
2. Thermal conductivity measurements of high-strength concrete Mix 5 measured at Orton (Appendix) using the hot-wire method (ASTM C 1113) are also somewhat similar to those of conventional strength normal weight concretes at ambient temperature; however, values decrease at higher temperatures. Measured values range from 18 Btu·in./h·ft²·°F (2.6 W/m·K) near ambient temperature to 4 Btu·in./h·ft²·°F (0.58 W/m·K) at temperatures approaching 1830°F (1000°C).
3. Values of thermal diffusivity of the high-strength concretes measured at CTL using the guarded hot plate apparatus are also similar to those for conventional strength normal weight concretes. Measured values range from 0.023 to 0.029 ft²/h (0.58 to 0.74 mm²/s) for tests at ambient temperature. The thermal diffusivity of the high-strength concrete decreases with increasing temperature. Measured values range from 0.020 to 0.025 ft²/h (0.51 to 0.65 mm²/s) at 255°F (125°C) and 0.014 to 0.017

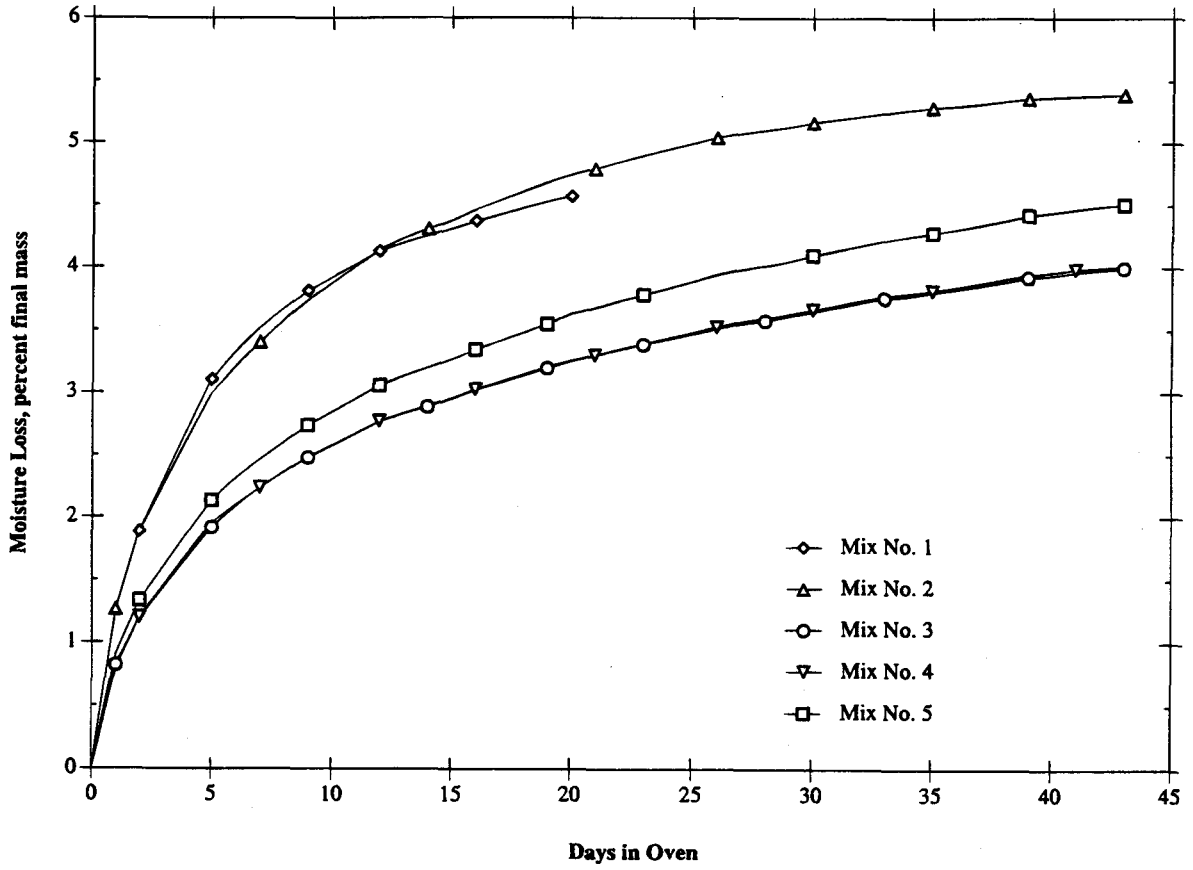


FIG. 9—*Moisture loss from high-strength concrete dried at 180°F (85°C).*

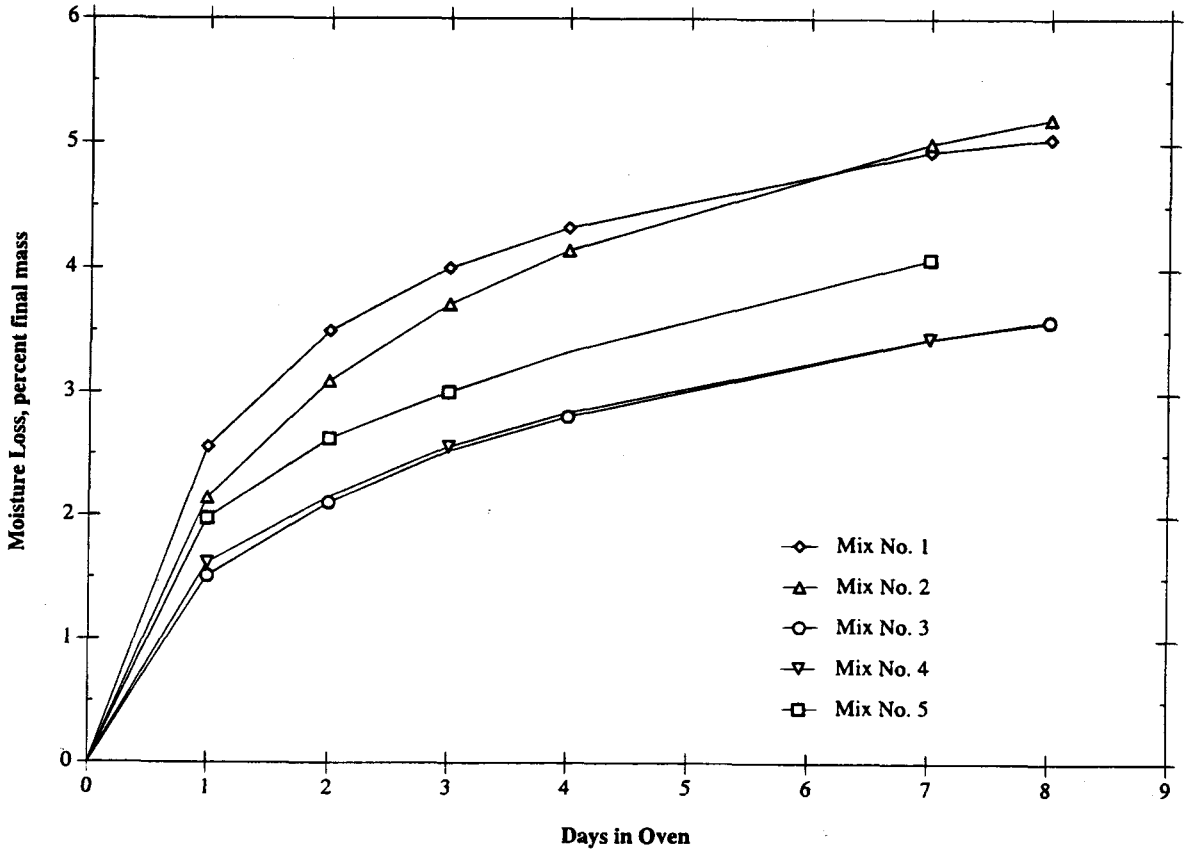


FIG. 10—*Moisture loss from high-strength concrete dried at 220°F (105°C) for 7 to 8 days.*

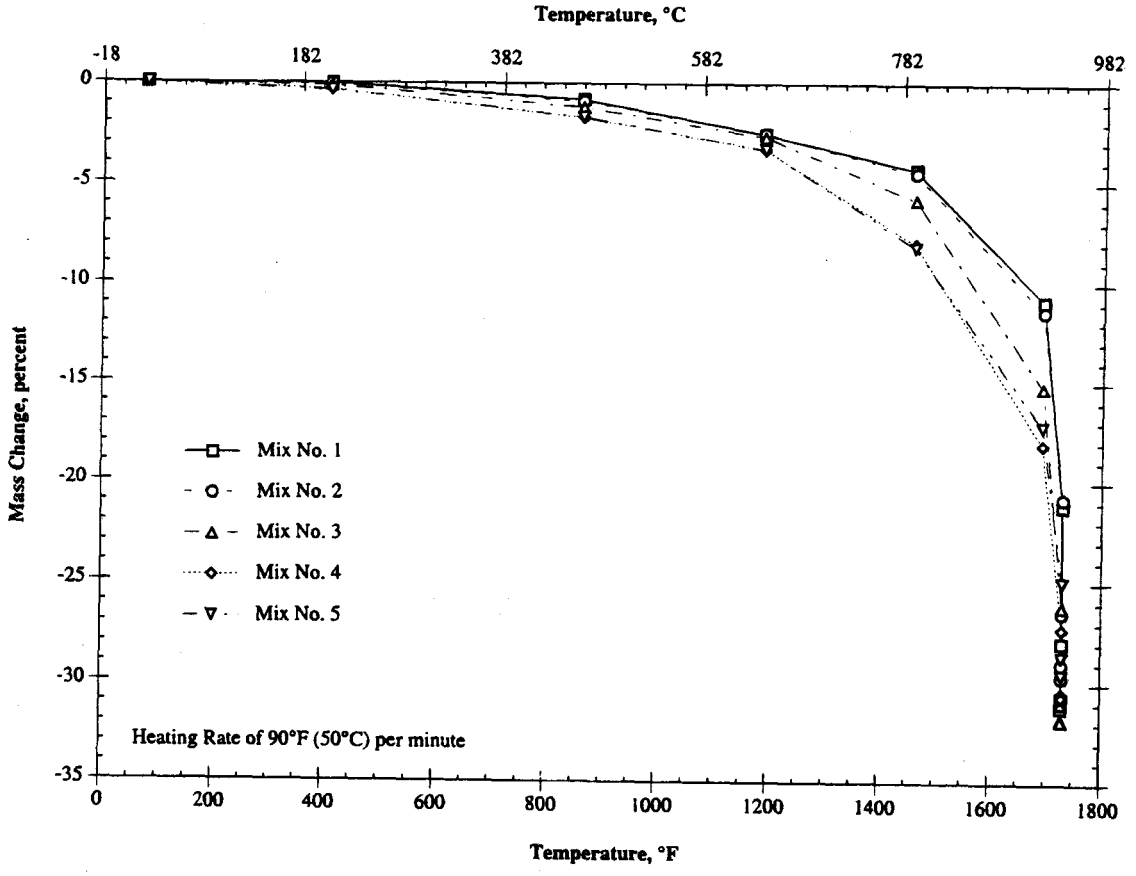


FIG. 7—*Mass loss of high-strength concrete at elevated temperatures.*

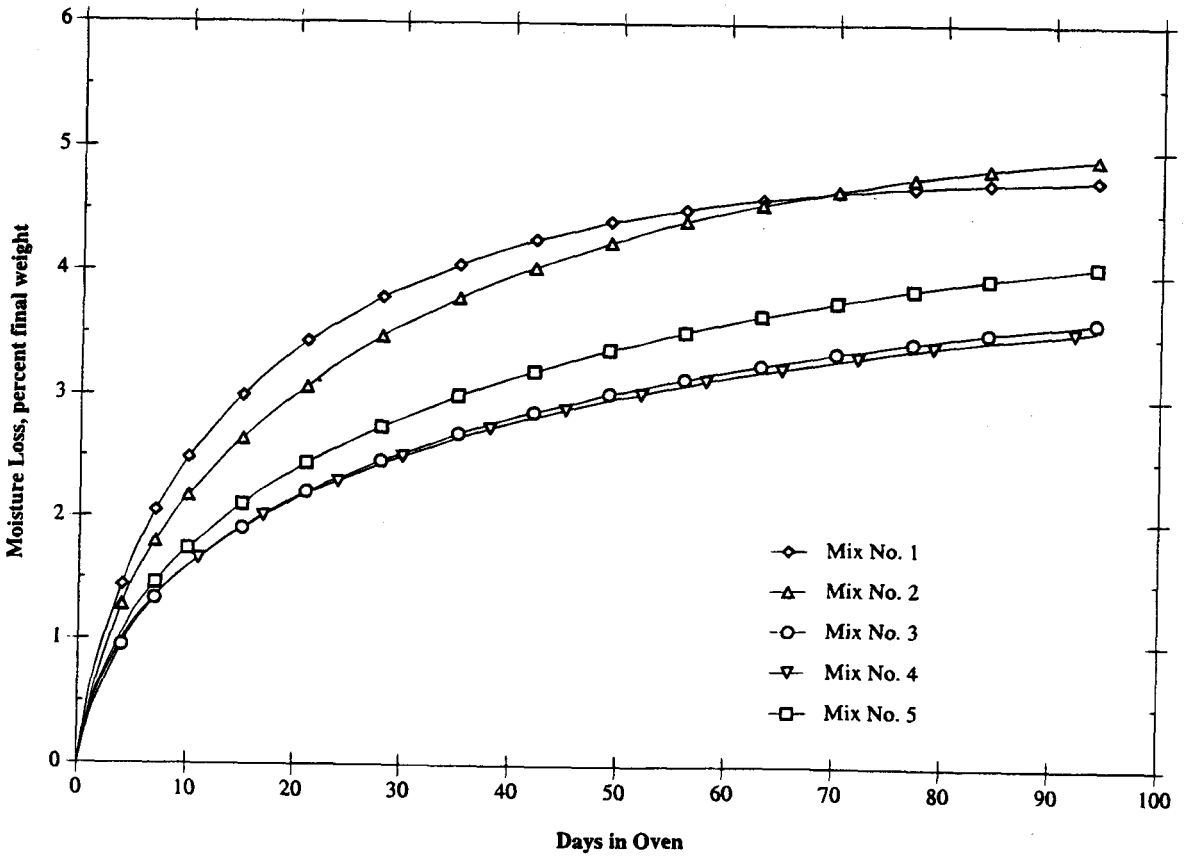


FIG. 8—*Moisture loss from high-strength concrete dried at 150°F (65°C).*

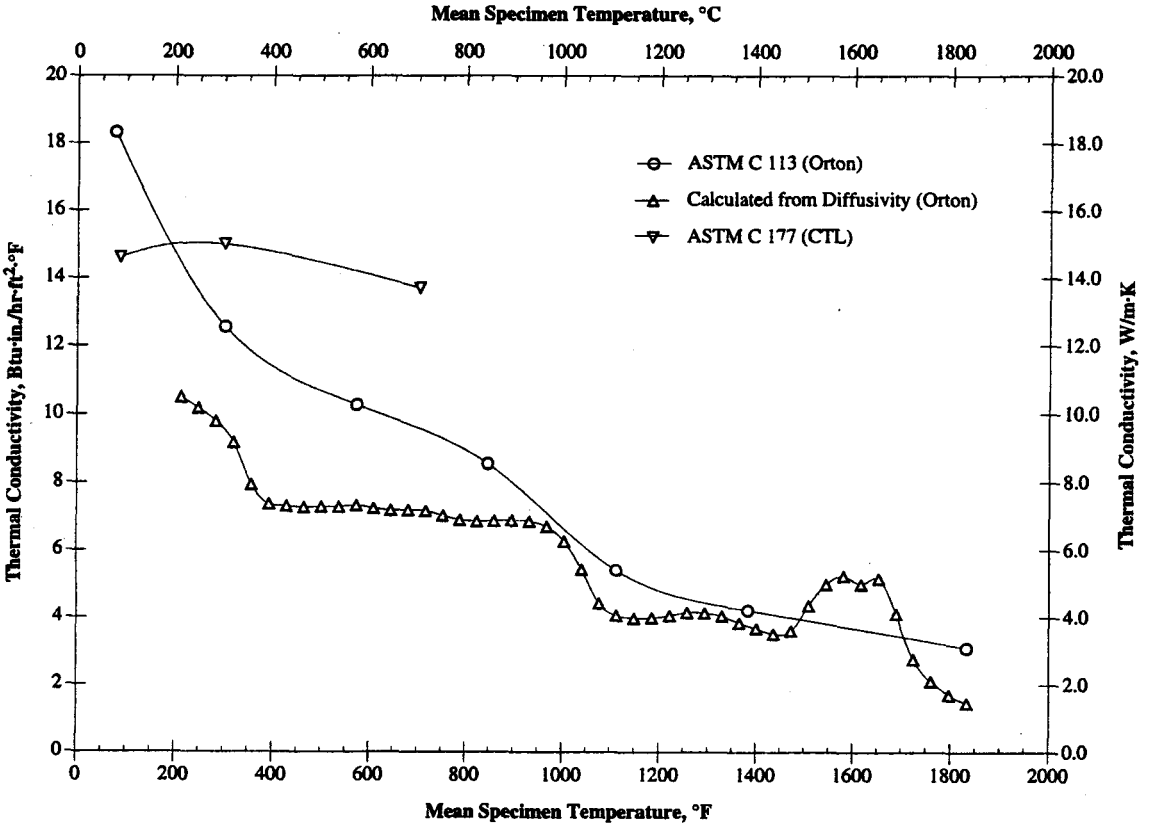


FIG. 12—*Thermal conductivity test results for oven-dried high-strength concrete Mix No. 5.*

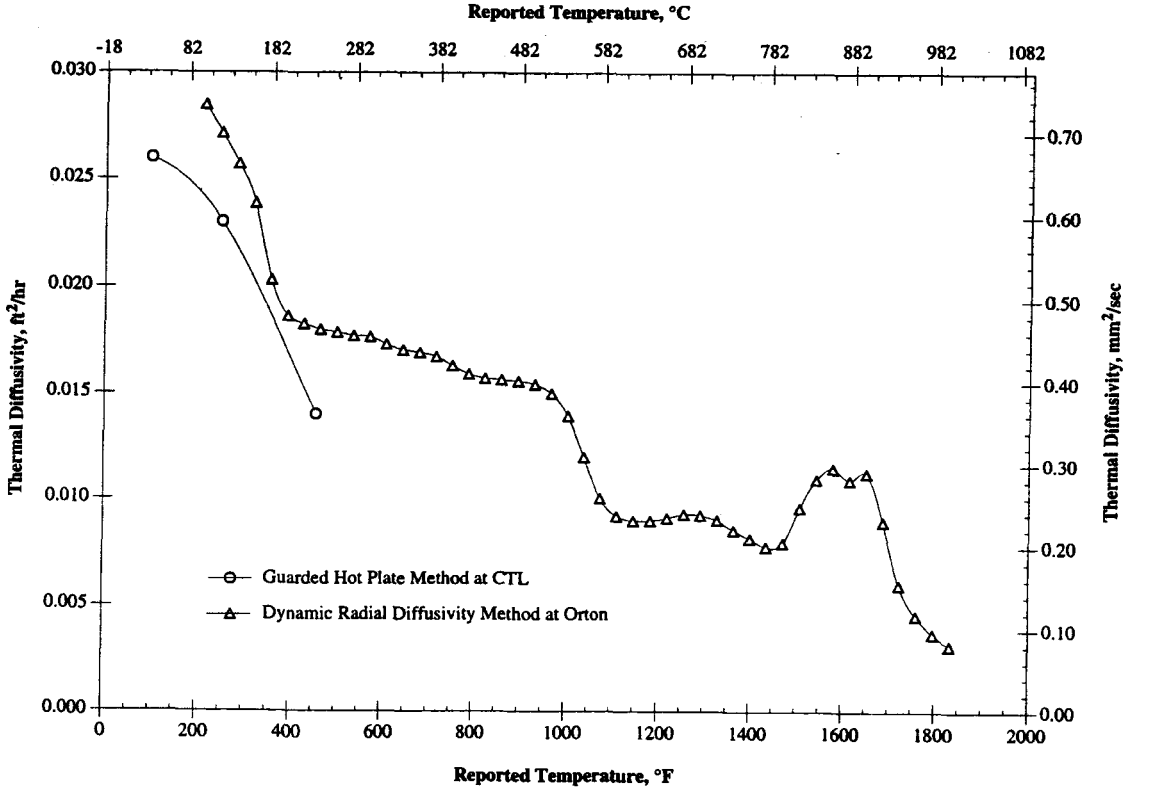


FIG. 13—*Thermal diffusivity test results for oven-dried high-strength concrete Mix No. 5.*

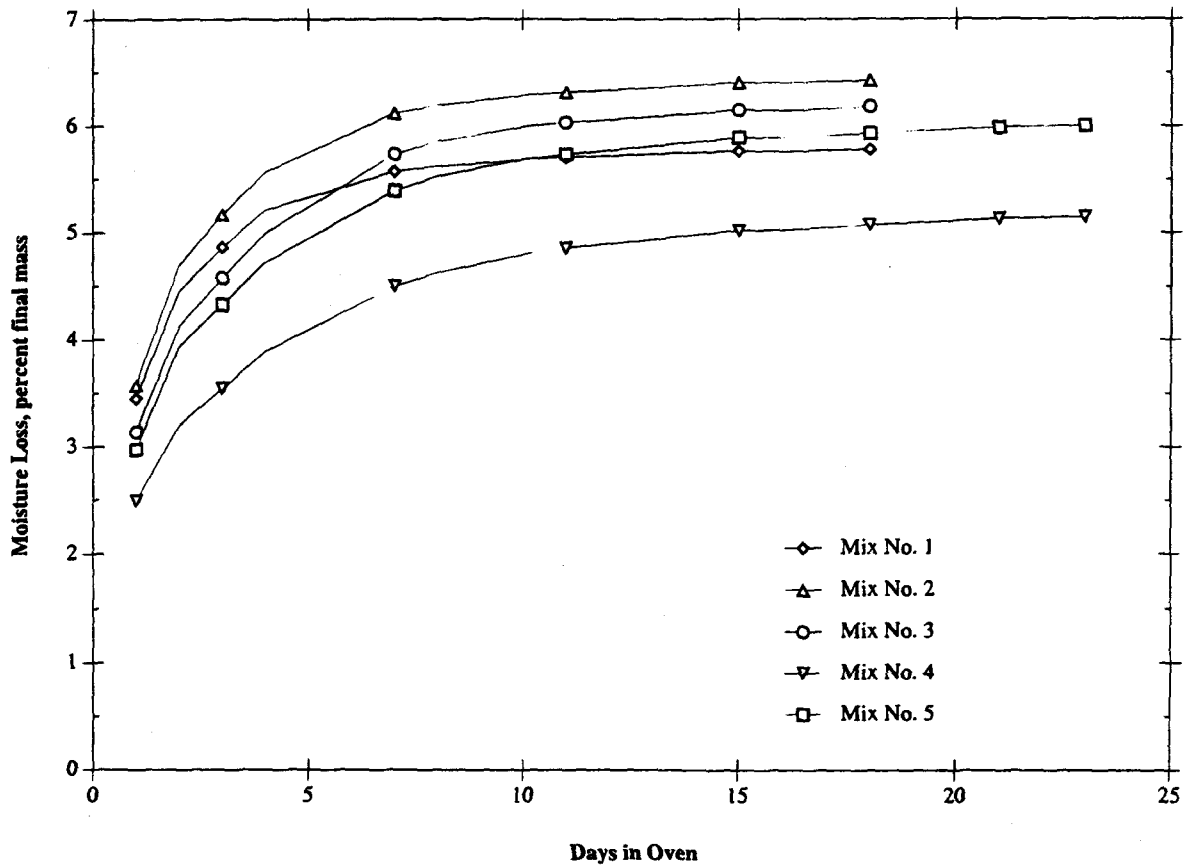


FIG. 11—*Moisture loss from high-strength concrete dried at 220°F (105°C) for 18 to 23 days.*

TABLE 10—*Moisture and mass loss from high-strength concrete.*

Mix.	Final Moisture Loss, % Final Mass: 150°F (65°C) for 84 days	180°F (85°C) for 43 days	220°F (105°C) for 8 days	220°F (105°C) for 18 days[a]	Mass Loss by TGA[b] at 1740°F (950°C), % Oven-Dry Mass	Initial Water Content,[c] %
1	4.7	4.6[d]	5.0	5.8	31	8.7
2	4.8	5.4	5.2	6.4	30	8.7
3	3.5	4.0	3.6	6.4	32	8.6
4	3.5	4.0	3.6	5.1	31	7.8
5	4.0	4.5	4.1[e]	6.0	30	8.1

[a]Specimens from Mixes 4 and 5 were oven-dried for 23 days.
[b]Oven-dried at 220°F (105°C) before testing.
[c]Quantity of water in mix, including water in admixtures and aggregate, divided by quantity of dry materials.
[d]Oven-dried for 20 days.
[e]Oven-dried for 7 days.

ft^2/h (0.35 to 0.44 mm^2/s) at 480°F (250°C). This trend of decreasing values with increasing temperatures also occurs for conventional-strength normal-weight concretes.

4. Thermal diffusivity of the high-strength concretes measured using a dynamic radial heat flow method at Orton also decrease with increasing temperatures. Measured values range from 0.029 ft^2/h (0.74 mm^2/s) near ambient temperature to 0.003 ft^2/h (0.08 mm^2/s) at temperatures approaching 1830°F (1000°C). The diffusivity dramatically decreases at temperatures of 1000°F (540°C), corresponding to the release of carbon dioxide observed in the increased rates of mass loss near this temperature.

5. Ambient temperature specific heat values for the high-strength concretes in the SSD, normally dry, and oven-dry conditions are similar to those for conventional strength normal weight concretes. Typical values for conventional strength concretes range from 0.19 to 0.24 Btu/lb·°F (790 to 1000 J/kg·K). Measured values of specific heat for the high-strength concretes are not significantly different from each other and are in the high end of the range for conventional strength concretes.

6. The mass loss of high-strength concretes at elevated temperatures is similar to that of conventional strength concretes with calcareous aggregate. Approximately 30% of the mass of the con-

crete is lost as the temperature of the concrete approaches 1830°F (1000°C). Mass loss at a heating rate of 4°F (2°C) per min was significantly increased compared to that at a heating rate of 36°F (20°C) or 90°F (50°C) per min.

7. The amount of time to oven dry the high-strength concretes to a constant mass increased at lower drying temperatures.

Acknowledgment

The research presented in this paper was conducted at Construction Technology Laboratories, Inc., unless otherwise noted, with the sponsorship of the Portland Cement Association. The contents of this paper reflect the views of the authors, who are responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the views of the Portland Cement Association.

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Appendix

Additional Thermal Conductivity and Thermal Diffusivity Test Results

Thermal Conductivity

Thermal conductivity was measured directly by Orton Refractories Testing and Research Center in general accordance with ASTM C 1113, Standard Test Method for Thermal Conductivity of Refractories by Hot-Wire (Platinum Resistance Thermometer Technique). High-strength concrete Mix No. 5 specimens were used for this testing. Specimens were cast in 6- by 12-in. (150- by 300-mm) cylinder molds in Nov. of 1989 and stored for 28 days in the moist room. After moist curing, specimens were stored at 72 ± 4°F (22 ± 2°C) and 50 ± 6% relative humidity for approximately 71 months. Specimens were wrapped in plastic and shipped to Orton for processing and testing. A 6-in. (150-mm) diameter by 9-in. (230-mm) long cylinder, split lengthwise was prepared and ovendried for 24 h at 212°F (100°C) for the ASTM C 1113 testing. Thermal conductivity measurements were performed at 70, 300, 570, 840, 1110, 1380, and 1830°F (25, 150, 300, 450, 600, 750, and 1000°C). Prior to each thermal conductivity measurement, the temperature of the cylinder was held constant for approximately 6 h (Fig. 12).

Thermal Diffusivity

Thermal diffusivity was measured directly by Orton Refractories Testing and Research Center using a dynamic radial heat flow method. Measurements were performed on a commercially available Thermal Conductivity/Conductivity Analyzer (DCA) on the previously described high-strength concrete Mix No. 5 specimens. A $2^1/_8$-in. (55-mm) diameter by $5^1/_2$-in. (140-mm) long cylinder was prepared and oven-dried for 24 h at 212°F (100°C) by Orton personnel for this testing. The cylinder contained two holes for thermocouples; one near the outside edge and the other near the centerline of the cylinder. Thermal diffusivity was measured continuously from 210 to 1830°F (100 to 1000°C) at a heating rate of 2.7°F (1.5°C) per minute. Thermal conductivity was calculated from the thermal diffusivity using bulk thermal properties of chemical components (measured at CTL by X-ray fluorescence) of high-strength concrete Mix No. 5 (Fig. 13).

Remarks

Thermal conductivity and thermal diffusivity measurements are method dependent, therefore, results obtained by CTL and Orton are not directly comparable. Thermal conductivity and thermal diffusivity data from Orton, converted to the appropriate units and format are presented in Figs. A1 and A2.

Thermal conductivity measurements of high-strength concrete Mix No. 5 measured by Orton using the hot-wire method (ASTM C 1113) are somewhat similar to those of conventional strength normal weight concretes at ambient temperature; however, values decrease at higher temperatures (Abrams 1980). Measured values range from 18 Btu·in./h·ft²·°F (2.6 W/m·K) near ambient temperature to 4 Btu·in./h·ft²·°F (0.58 W/m·K) at temperatures approaching 1830°F (1000°C).

Thermal diffusivity of the high-strength concretes measured using a dynamic radial heat flow method at Orton decrease with increasing temperatures. Measured values range from 0.029 ft²/h (0.74 mm²/s) near ambient temperature to 0.003 ft²/h (0.08 mm²/s) at temperatures approaching 1830°F (1000°C). Thermal diffusivity test results of siliceous aggregate concrete, presented by Abrams (1980), are similar to thermal diffusivity measurements by Orton on Mix No. 5. At temperatures below 930 to 1110°F (500 to 600°C), the shape of the thermal diffusivity versus temperature curves are nearly identical. Above this temperature range, the shape of the curves differs. This is in part due to the difference in aggregate between the concrete specimens.

Orton required one specimen be pre-fired at CTL to 1830°F (1000°C) at a heating rate of 4°F (2°C) per min prior to testing to ensure physical stability of the specimens at elevated temperatures. As a result of firing, the cementitious material paste (portland cement, silica fume, and fly ash paste) changed color from dark gray to white. Within seven days of exposure to normal room temperature and humidity conditions, the fired concrete specimen expanded to approximately 120% of its post-fired size and gradually fell apart.