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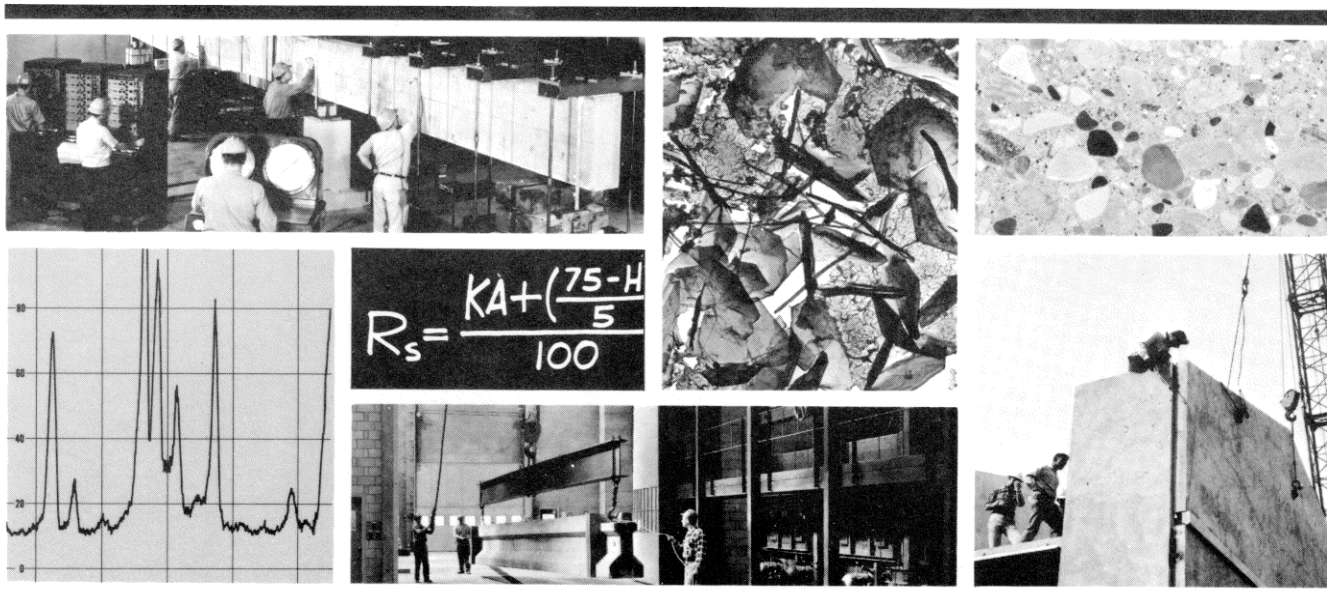

Compressive Strength of Concrete at Temperatures to 1,600F

by M. S. Abrams

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PORTLAND CEMENT PCA ASSOCIATION

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SYNOPSIS

Compressive strength tests were conducted on 3x6-in. (7.5x15-cm) cylindrical specimens heated for short duration to temperatures of 200 to 1,600 F (93 to 871 C). Variables included aggregate type (carbonate, siliceous, and lightweight), test procedure (heated without load and tested hot, heated with load and tested hot, and tested cool after heating), and original strength of concrete (3,300 to 6,500 psi—230 to 455 kg/cm^2). Carbonate aggregate concrete and lightweight concrete tested hot without prior loading retained about 75 percent of their original strengths (strengths prior to heating) at 1,200 F (649 C). Above that temperature, lower strengths were obtained. Specimens heated while loaded had the highest strengths, while strengths of specimens heated, cooled, and then tested were the lowest throughout the temperature range. Original strength of concrete had little effect on the percentage of strength retained at high temperatures. The sanded lightweight concrete had strength characteristics at high temperatures similar to those of carbonate concrete. At temperatures above 800 F (427 C), the siliceous aggregate concrete had lower strengths than the other concretes.

Keywords: aggregates, carbonate aggregates, compressive strength, concretes, expanded shale aggregates, fire resistance, high temperature tests, lightweight aggregate concretes, lightweight aggregates, petrography, plain concrete, research, siliceous aggregates.

In recent years progress has been made toward the development of rational methods for calculating the behavior of concrete structures subjected to fire or to other high-temperature-exposure conditions. It is now possible to calculate the fire endurance of simply supported prestressed concrete beams and slabs with a reasonable degree of accuracy.[1]** For simply supported members, differences in the strength of concrete in the compressive zone caused by fire are relatively minor and do not significantly affect the fire endurance. However, in the design for fire resistance of continuous beams or slabs, restrained floors or roofs, or more complex frames, data on the compressive strength of concrete at high temperatures are often needed.[2] At these temperatures the concrete materials may undergo transformations such as calcination of carbonate aggregates, abrupt expansion due to inversion of quartz, or dehydration of cement paste. Such transformations are likely to affect strength of concrete. This program was undertaken to develop additional desired information.

Test conditions were selected to simulate a variety of exposure environments likely to occur in a fire of several hours duration. Some tests were intended to simulate conditions of concrete under no initial stress (unstressed) and exposed to high temperatures. Other tests (stressed) simulated concrete in columns or compressive zones of flexural members subjected to heat. In addition, some tests (unstressed residual) were intended to yield information on strength of unstressed concrete that had been exposed to fire.

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**Superscript numbers in parentheses designate references at the end of this bulletin.

TEST PROGRAM

Specimens

Specimens were concrete cylinders 3 in. (7.5 cm) in diameter by 6 in. (15 cm) in height. They were cast in groups of 11—four for high-temperature tests, six for room-temperature tests, and one for monitoring humidity. The high-temperature test specimens contained three thin-wire, butt-welded thermocouples along the axis, one at the middle and one 1/2 in. (1.3 cm) from each end, Fig. 1. Thermocouples were positioned within 1/32 in. of the desired location. Positioning was accomplished by drawing the wire taut diametrically through specially designed steel molds in which the concrete was cast. The specimen used for humidity control contained a Monfore-type humidity well[3] along the axis of the cylinder.

Materials

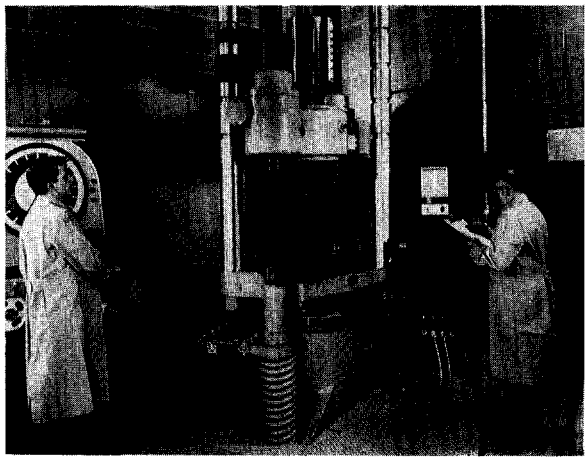
One of the variables was the type of aggregate. A carbonate, a siliceous, and an expanded-shale lightweight aggregate were included. In each case the maximum size was 3/4 in. (2 cm). The carbonate aggregate was a dolomitic sand and gravel from Elgin, Ill., while the siliceous aggregate was sand and gravel from Eau Claire, Wis. Petrographic descriptions of the three aggregates are given in the appendix to this report. Each sand was air-dried, screened into six size fractions, and recombined prior to batching in the proportions shown in Table 1.

A blend of four Type I cements from different sources was used.

Three different concretes were used, each with two strength levels. Data on the concrete mixtures are given in Table 2. The two lightweight concrete mixes contained sand from Elgin, Ill., and are referred to throughout the text as sanded lightweight concrete.

Specimen Preparation

Each 11-specimen group was made from a 0.7 cu ft (20 liter) batch. Concrete was consolidated in steel molds in three lifts on a table vibrator. Specimens were cured under damp burlap at 70 to 75 F (21 to 24 C) for 24 hours, after which they were removed from the molds and stored in a fog room for 6 days. Ends of the specimens were ground plane. Specimen cylinders were then stored in an atmosphere of 30 to 40 percent RH and 70 to 75 F (21



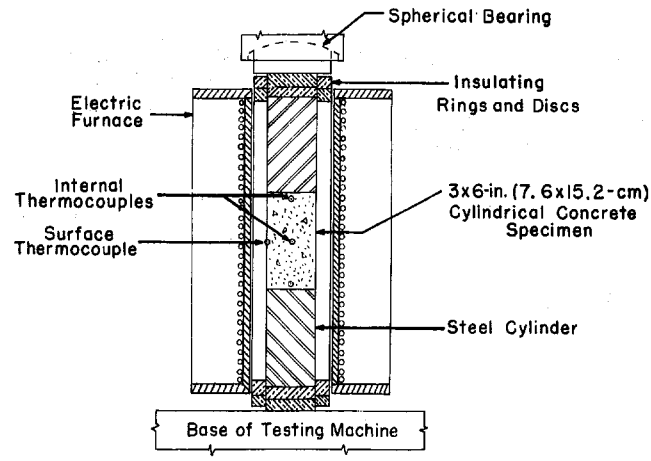


Fig. 1. Arrangement of test equipment.

TABLE 1. Grading of Aggregates

Sieve size	Percent retained						
	Carbonate[a]		Siliceous[b]		Expanded shale[c]		
	Sand	Gravel	Sand	Gravel	Fine	Medium	Coarse
3/4 in.	–	0	–	0	–	–	0
3/8 in.	–	50	–	50	–	1	78
No. 4	1	100	1	100	0	56	99
8	14	–	14	–	20	93	–
16	23	–	23	–	51	–	–
30	45	–	45	–	75	–	–
50	75	–	75	–	90	–	–
100	98	–	98	–	96	–	–
Fineness modulus	2.56	–	2.56	–	3.33	–	–

[a]Sand and gravel from Elgin, Ill.
[b]Sand and gravel from Eau Claire, Wis.
[c]Rotary-kiln-produced expanded shale from Ottawa, Ill.
Note: Carbonate and siliceous aggregates were screened into individual sieve size fractions and recombined as indicated.

to 24 C) until the relative humidity at the center of the monitor specimen reached 75 percent. A period of 3 to 6 weeks was required depending on aggregate type and concrete strength. To prevent further drying, specimens not tested immediately after reaching 75 percent RH were placed in air controlled at 70 to 80 percent RH and 70 to 75 F (21 to 24 C) until test. Some specimens of Mixes I, III, and V were dried at 230 F (110 C) to constant weight.

Test Procedures

Fig. 1 shows the test setup. Steel cylinders 3 in. (7.5 cm) in diameter by 6 in. (15 cm) long with machined ends were used to transmit the load from the testing machine to the specimen. To prevent excessive heat flow away from the specimen, two cement-asbestos insulating discs were placed between the steel cylinders and the testing machine. Prior to use, the discs were compressed with a load equivalent to about 1.5 times the concrete strength. This effectively prevented excessive deformation of the discs under load. Insulating rings of the same material were used to minimize heat loss. The arrangement effectively maintained a nearly uniform temperature throughout the specimen length.

Temperatures of the concrete were monitored throughout each test. In addition to the three internal thermocouples, a fourth one was attached to the surface of the specimen at midheight. Tests were performed at various temperatures between 70 and 1,600 F (21 to 871 C). During heating, the temperature difference within the specimen, as measured by the thermocouples, was restricted to 150 F (83 C) by controlling the heat output of the electric furnace. When the surface of the concrete reached the test temperature, the specimen was allowed to equilibrate until the temperature was essentially uniform vertically and radially. For test temperatures up to 600 F (316 C), compression tests were not conducted until the maximum difference among the four thermocouple readings was within 20 F (11 C). For higher test temperatures, the difference was limited to 3 percent of the test temperature in Fahrenheit degrees. In general 3 to 4 hours were required to achieve a uniform test temperature within the specimen.

From each group of specimens, four were heated and tests were performed in one of three ways:

Unstressed. Specimen was heated to the test temperature in an unloaded condition and then loaded to failure.

Stressed. A compressive load was maintained on the specimen during heating. When the test temperature was reached, the load was increased until failure occurred. Prior to performing the high-temperature test, the strength at room temperature, f'_c, was determined by testing the companion specimens. Stressed tests were performed at stress levels, f_c, of 0.25, 0.40, and 0.55 f'_c. Room-temperature strength tests were made with the same equipment as that used for heated tests.

TABLE 2. Data on Concrete Mixes

Item	Mix I	Mix II	Mix III	Mix IV	Mix V	Mix VI
	Carbonate aggregate[a] concrete		Siliceous aggregate[b] concrete		Sanded lightweight[c] concrete	
Batch quantities, pounds per cubic yard (kg/m^3)						
Cement	398 (237)	534 (317)	419 (249)	555 (330)	444 (264)	588 (350)
Coarse aggregate	1,825 (1,085)	1,675 (995)	1,810 (1,080)	1,680 (1,000)	525 (312)	515 (306)
Medium aggregate	–	–	–	–	305 (181)	295 (176)
Fine aggregate	–	–	–	–	410 (244)	585 (348)
Sand	1,440 (855)	1,465 (870)	1,435 (855)	1,475 (880)	870 (518)	555 (330)
Water	218[d] (130)	226[d] (134)	214[d] (127)	221[d] (132)	346[e] (206)	346[e] (206)
Average air content, percent	6.0	5.6	5.0	5.0	5.9	6.4
Average unit weight, pcf (kg/m^3)	144 (2,310)	144 (2,310)	144 (2,310)	146 (2,340)	107 (1,720)	107 (1,720)
Average compressive strength at test (unheated specimens), psi (kg/cm^2)	3,900 (275)	5,600 (395)	3,900 (275)	5,500 (385)	3,900 (275)	6,300 (445)

[a] 3/4 in. (nom. 2 cm) maximum-size gravel and sand from Elgin, Ill.
[b] 3/4 in. (nom. 2 cm) maximum-size gravel and sand from Eau Claire, Wis.
[c] Rotary-kiln-produced expanded shale from Ottawa, Ill., and sand from Elgin, Ill.
[d] Based on saturated surface-dry aggregates.
[e] Based on dry aggregates.

Unstressed residual. The specimen was heated in an unloaded condition to test temperature and allowed to cool slowly (generally overnight) to room temperature. The specimen was then stored in air at 70 to 80 percent RH and 70 to 75 F (21 to 24 C) for 7 days. Both the residual-strength specimens and their companion control specimens were tested in accordance with ASTM C39.[5]

Specimens from the same group were tested at 70 F (21 C) within two days of the tests of their companion heated specimens.

DISCUSSION OF TEST RESULTS

Table 3 is a summary of the test program and shows the number of compression tests performed for each test condition. At least two tests were performed for each condition. In many instances, three to seven tests were conducted. All of the results for any specific test condition were used in determining the average strength for that condition. Good agreement was obtained among results for each test condition. For the 148 conditions at elevated temperatures the results, expressed in terms of the room-temperature strength, differed by less than 5 percent in 74 cases, 6 to 10 percent in 30 cases, 11 to 20 percent in 34 cases, and greater than 20 percent in 10 cases. Three or more tests were performed in nearly all instances when the difference in results exceeded 10 percent.

Other investigators have reported on differences in compressive-strength test results at high temperatures. Harmathy and Berndt[6] noted from studies on mortar and lightweight concrete that specimens assumed to be identical and subjected to the same test condition often yielded differences in results of the order enumerated above.

Results of other studies are cited in the discussion that follows. In general, direct comparisons of results of different studies are difficult to interpret because of differences in testing, materials, and specimen size.

Effect of Test Procedures

Carbonate aggregate concrete—Mix I. Fig. 2 shows the effect of temperature on compressive strength of carbonate aggregate concrete, Mix I, for three conditions of test: unstressed, stressed to 0.40 f'_c, and unstressed residual. Strengths of the unstressed specimens diminished gradually from that at room temperature until at 1,200 F (649 C) the concrete retained about 75 percent of its original strength. At 1,400 F (760 C) the strength remained above 50 percent but it declined significantly at higher temperatures, probably owing to calcination of the carbonate aggregates.[7] Strengths were higher over the entire temperature range for specimens stressed to 0.40 f'_c during heating; at 1,200 F (649 C) the strength was about the same as the original strength; and at 1,400 F (760 C) the carbonate aggregate concrete retained 80 percent of its original strength. The greatest losses in strength were recorded in the unstressed residual tests.

Siliceous aggregate concrete—Mix III. Fig. 3 shows the influence of temperature on compressive strength of concrete made with siliceous aggregate for the various test procedures. In the unstressed condition the concrete retained 75 percent of its original strength at 850 F (454 C), 50 percent at 1,000 F (538 C) and 25 percent at 1,300 F (704 C). The relatively high thermal expansion of siliceous rocks and the abrupt volume change that accompanies the inversion of quartz from the α to β form at about 1,060 F (571 C) probably account for this decrease in strength. It should be noted, however, that at 1,060 F (571 C) there is not an abrupt change in strength.

Stressing the concrete had a beneficial effect over the entire temperature range, particularly between 800 and 1,400 F (427 and 760 C). Malhotra[8] has attributed the smaller strength loss under the

TABLE 3. Number of Compression Tests Performed for Each Condition

Strength range, psi (kg/cm²)	3,410 to 4,330 (240 to 305)					3,310 to 4,660 (230 to 330)					3,420 to 4,630 (240 to 325)				
Aggregate	Carbonate[a]					Siliceous[b]					Sanded lightweight[c]				
Type of test[d]	U	Stressed			R	U	Stressed			R	U	Stressed			R
Stress level during heating, f_c/f'_c	0	0.25	0.40	0.55	0	0	0.25	0.40	0.55	0	0	0.25	0.40	0.55	0
Temperature, F (C)															
70(21)	45	12	45	12	18	50	18	50	6	18	30	12	40	12	18
200(93)	2		2			2		2			2		2		
400(204)	4	4	3	2	3	4	2	5	2	2	3	2	4	2	2
600(316)	4		3			4		4			3		7		
700(371)					2					2					3
800(427)	4		3			3		5			5		6		
900(482)		2		2		2	2	5	2	2		2		2	
950(510)						4		4							
1,000(538)	4		4		2	4		4		2	7		7		2
1,200(649)	4		4			3		4			5		5		
1,300(704)	3	2	4	2	2	2	4	2		2	2	2	2	2	2
1,400(760)	2		4		2	2	3				2		2		
1,500(816)	2		2			2	3				2		2		
1,600(871)	2		2			2	2				2		2		2
Strength range, psi (kg/cm²)	5,310 to 6,340 (375 to 445)					5,380 to 5,720 (380 to 400)					6,000 to 6,500 (420 to 455)				
70(21)	18	12	12	12	12	12	12	12	6	12	12	12	12	12	12
400(204)	3	2	2	2	2	2	4	3	2	2	2	2	2	2	2
900(482)	3	2	2		2	2	2	2	2	2	2	2	2	2	2
1,000(538)				2											
1,200(649)								2							
1,300(704)	2	2	2	2	2	2	2	2		2	2	2	2	2	2
1,400(760)					2										
1,600(871)	2		2			2					2		2		2

[a] 3/4-in. (2-cm) maximum-size gravel and sand from Elgin, Ill.
[b] 3/4-in. (2-cm) maximum-size gravel and sand from Eau Claire, Wis.
[c] Rotary-kiln-produced expanded shale from Ottawa, Ill., and sand from Elgin, Ill.
[d] U = Unstressed; R = Unstressed Residual.

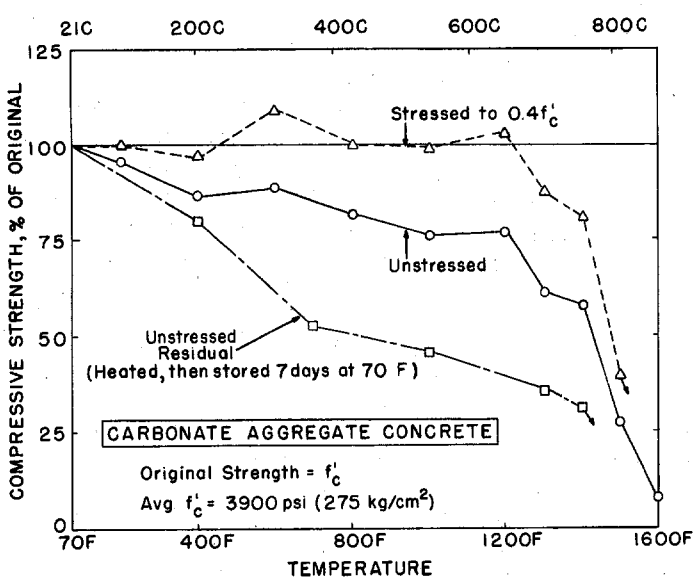


Fig. 2. Effect of temperature on compressive strength of carbonate aggregate concrete.

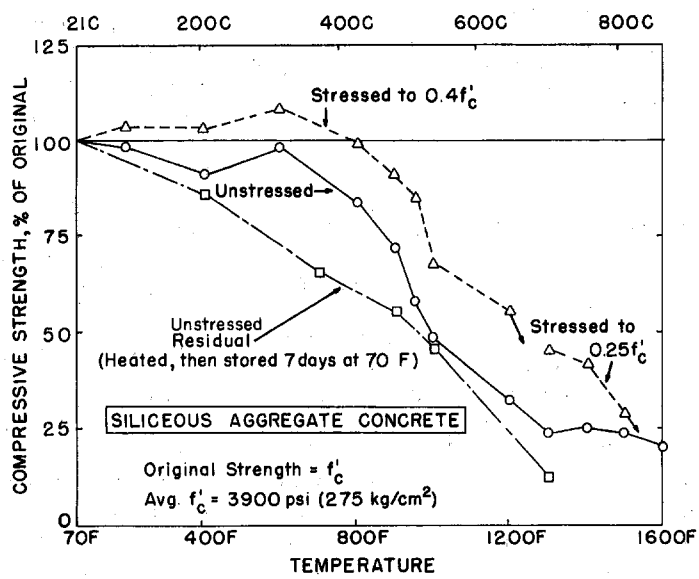


Fig. 3. Effect of temperature on compressive strength of siliceous aggregate concrete.

stressed condition to a retardation of crack formation.

The unstressed residual strength of the siliceous aggregate concrete was lower than the strength at high temperatures over the entire temperature range. The residual strength declined gradually to a value of 55 percent of original at 900 F (482 C). At higher temperatures, the rate of strength loss was greater.

Sanded lightweight concrete–Mix V. Fig. 4 shows the strength-temperature relationships for Mix V concrete specimens. Specimens stressed to 0.40 f'_c yielded higher strengths than unstressed specimens at temperatures above 700 F (371 C). At 1,300 F (704 C) the sanded lightweight concrete retained more than 70 percent of its original strength and at 1,500 F (816 C), more than 40 percent. The unstressed residual strengths were lower than the strengths at high temperatures for the sanded lightweight concrete, reflecting the same pattern as the two normal-weight concretes.

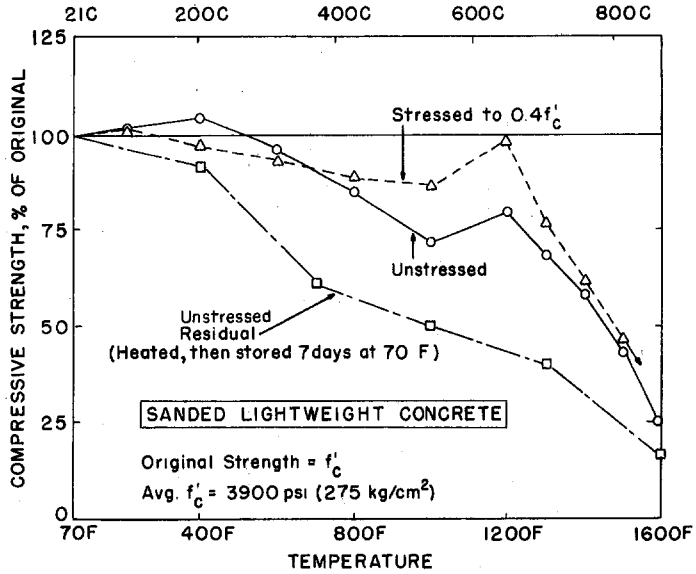


Fig. 4. Effect of temperature on compressive strength of sanded lightweight concrete.

General comments. For all three concretes, specimens stressed during heating retained the highest strengths at high temperatures. Specimens heated while stressed and tested hot had strengths 5 to 25 percent higher than companion specimens that were unstressed during heating. Even so, the carbonate aggregate concrete and the sanded lightweight concrete retained over 70 percent of their original strengths at 1,250 F (677 C) when tested by the unstressed procedure. The siliceous aggregate concrete retained 70 percent of its strength at 900 F (482 C) when tested unstressed. For all three concretes, unstressed residual strengths were lower than the "hot" strengths.

The above observations concerning the influence of test procedure generally agree with those reported by Malhotra,[8] whose tests extended to about 1,100 F (593 C). However, in the present study the strength reductions were smaller for all three conditions of test. Results of the unstressed sanded lightweight concrete agree closely with those reported by Harmathy and Berndt[6] for a similar concrete tested at temperatures up to 1,400 F (760 C). Results of unstressed tests of carbonate aggregate concrete and sanded lightweight concrete agree with those obtained by Saemann and Washa[9] from 70 to 450 F (21 to 232 C) except at 200 F (93 C).

It appears that the testing technique used in the present study resulted in lower unstressed residual strengths than those obtained by other techniques. For example, Zoldners[10] reported unstressed residual strength results of 4x8 in. (10x20 cm) cylinders made of siliceous aggregate concrete and limestone (carbonate) aggregate concrete. After a 7-day moist-curing period followed by dry storage up to a year, the specimens were fired. Specimens were then cooled 24 hours to room temperature, desiccated 4 hours, and tested in compression. Zoldners' results were higher for specimens heated throughout a range of 68 to 1,472 F (20 to 800 C) than the unstressed residual strengths obtained in the present study. The difference in residual strengths is probably the result of the 7-day conditioning period in air at 70 to 80 percent RH in the present study. This observation is supported by the work of Weigler and Fischer[11] who reported that the strength of portland cement mortar heated to 1,022 F (550 C) and cooled to room temperature decreased as the storage period in air increased from 1 to 7 days. Weigler and Fischer reported strength increases in mortar specimens when stored in water after cooling. In the current investigation, residual strength tests were not performed on concrete that was stressed during heating. Results of such tests were reported by Weigler and Fischer[12] on concretes made with barite aggregate and quartz aggregate. They observed that the specimens stressed to 0.33 or 0.50 f'_c during heating to 842 F (450 C) had residual strengths equal to or greater than those of companion specimens not stressed during heating.

Effect of Oven Drying

As noted previously, most specimens were tested when the relative humidity reached 75 percent. However, the specimens that were tested at 200 F (93 C) were oven-dried at 230 F (110 C) to constant weight prior to testing. Preliminary work showed that at 200 F (93 C) a specimen with 75 percent RH did not dry completely or uniformly during a 3- or 4-hour heating period. In fact, the reading on a humidity control specimen was 85 percent after a 4-hour heating period, indicating that the evaporable moisture was redistributed during heating and cooling. The resulting moisture gradient probably caused the periphery of the cylinder to shrink more than the center, making the ends (which had been ground flat) convex. Work by Gonnerman[13] indicated that a very small degree of convexity of the ends of specimens can result in reductions in compressive strength of 35 percent or more. Preliminary tests performed in the present study with specimens dried to 75 percent RH yielded results that were 20 to 30 percent lower than subse-

quent tests conducted on over-dried specimens. However, at temperatures of 400 F (204 C) and higher no strength loss attributable to moisture gradients was observed.

Saemann and Washa[9] reported strength losses of about 20 percent at 200 F (93 C) on 6x12-in. (15x30-cm) concrete cylinders. Observations of samples of concrete from the broken cylinders indicated that moisture was still present after the 24-hour preconditioning period at 200 F (93 C). Binner et al.[14] indicated from work on high-density concrete that preconditioning periods of 7 or 14 days at 200 F (93 C) resulted in no loss of strength when the concrete was cooled and tested. Harmathy and Berndt[6] reported no loss in strength at 200 F (93 C) for lightweight concrete dried to constant weight at 221 F (105 C) prior to test.

Effect of Stress Intensity During Heating

Fig. 5 summarizes the data for all six concrete mixes on the effect of stress intensity during heating. It can be noted that in nearly every case, the stress level during heating had little effect on the compressive strength of concrete at any given test temperature. These results were independent of (a) original strength of the concrete, (b) aggregate type, and (c) test temperature. It is of interest to note that certain results of residual strength tests reported by Weigler and Fischer[12] were invariant under a critical load that ranged from 0.33 to 0.50 f'_c.

Effect of Original Compressive Strength

Fig. 6 summarizes the data that show the effect of original compressive strength on the strength determined by the three test methods (unstressed, stressed to 0.40 f'_c, and unstressed residual). It can be noted from the 32 comparisons that the original strength level of the concrete, within the ranges used in this study, has little effect on the percentage of compressive strength retained at elevated temperatures or after cooling. This observation appears to be independent of test procedure, aggregate type, or exposure temperature. Malhotra[8] and Weigler and Fischer[11] reported similar findings.

Effect of Aggregate Type

The data in Figs. 2, 3, and 4 have been replotted in Figs. 7, 8, and 9 to show the influence of aggregate type on compressive strength of concrete at high temperatures. In general, the three concretes exhibited similar strength-loss characteristics under each test condition to about 900 F (482 C). Above 900 F (482 C) the siliceous aggregate concrete retained less strength for all three test procedures. Concretes made with either the carbonate or sanded lightweight aggregates behaved about the same over the entire temperature range.

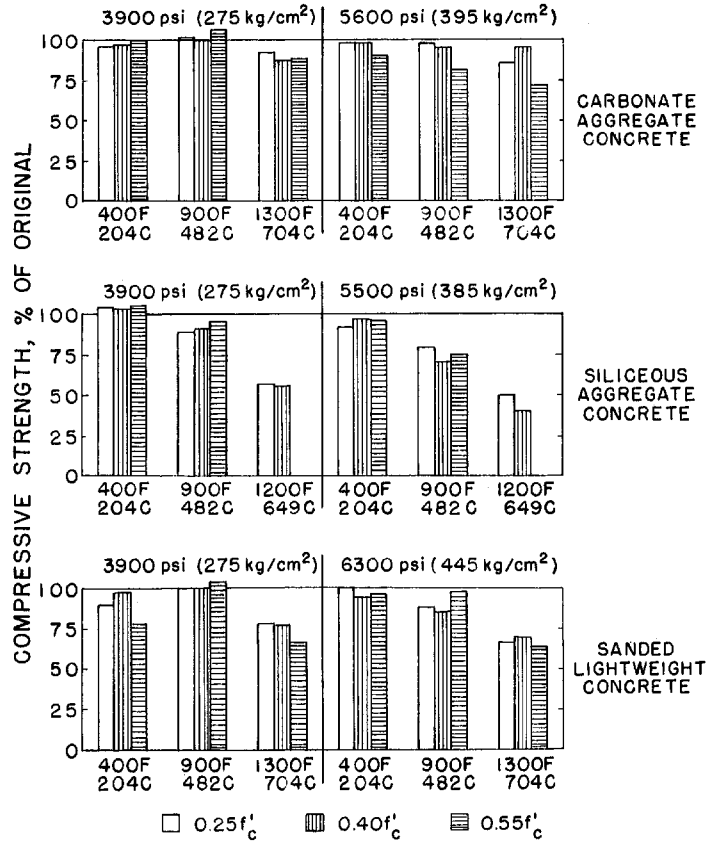


Fig. 5. Influence of stress level during heating on compressive strength at high temperatures.

Petrographic Examination of Heated Concretes

The high strengths retained by all three concretes at 900 F (482 C) and by the carbonate aggregate and sanded lightweight concretes at temperatures exceeding 1,200 F (649 C) suggest that the physical condition of the concretes was not significantly altered by heating to those temperatures. Specimens of Mixes I, III, and V were heated without load to various temperatures up to 1,500 F (816 C) and were allowed to cool for 24 hours. After cooling, specimens were encased in polyester resin and sawed in half longitudinally. The sawed surface was then ground and polished. Photographs of the polished surfaces are shown in Figs. 10, 11, and 12.

Carbonate aggregate concretes, Fig. 10, heated to 800 F (427 C) and lower were similar to the unheated concrete. In the specimen heated to 1,200 F (649 C), a small amount of mortar eroded around some particles of the sand during the sawing and polishing operations. The 1,500 F (816 C) specimen, which had a lower retained strength, exhibited a higher degree of mortar erosion around the aggregate particles, indicating more extensive loss of bond between the aggregate and paste. A longitudinal crack can be seen near the surface. However, the carbonate aggregate particles appear to be unaffected.

The siliceous aggregate concrete, Fig. 11, which retained 70 percent of its original strength when tested unstressed at 900 F (482 C), shows indications of

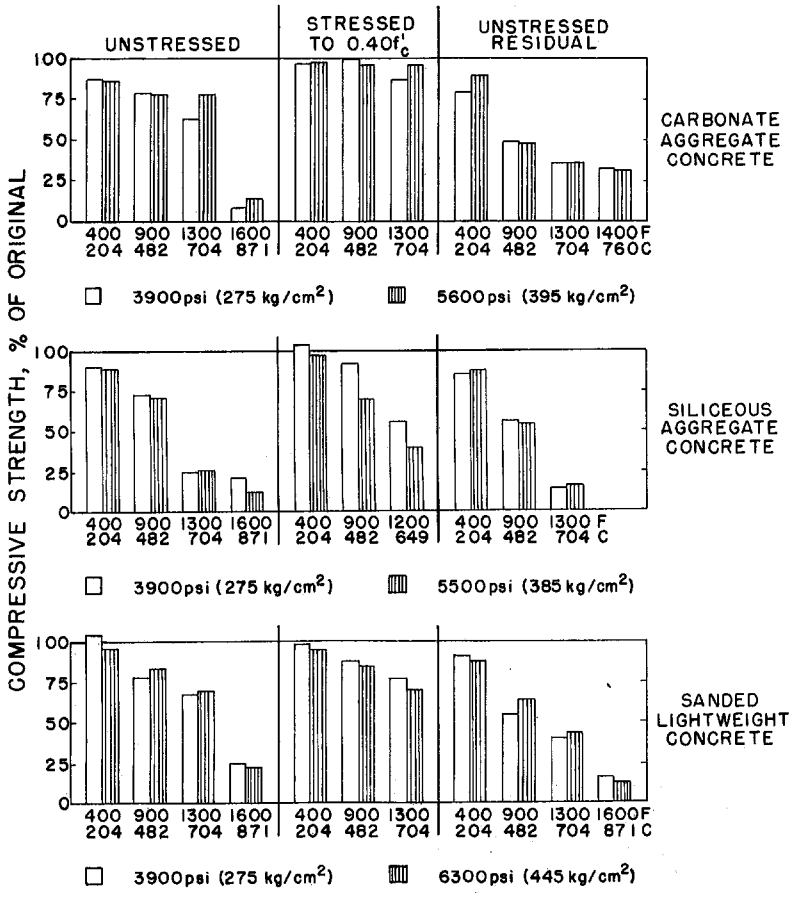


Fig. 6. Influence of original strength on compressive strength of concrete exposed to high temperatures.

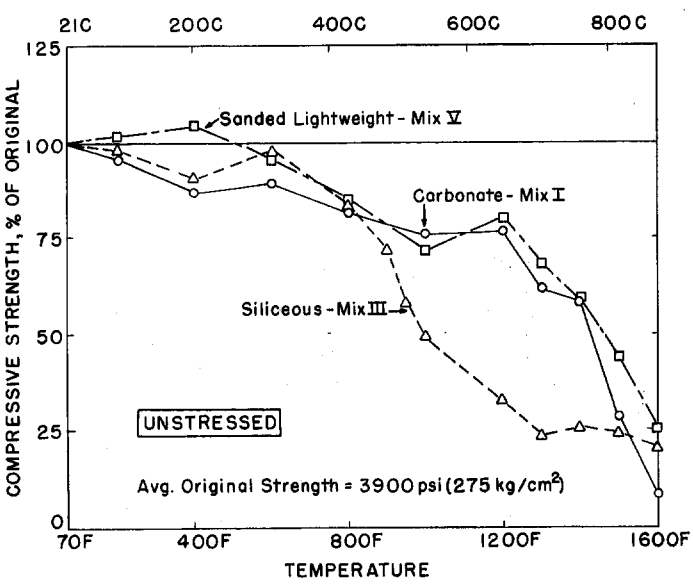


Fig. 7. Effect of aggregate type on compressive strength of concrete tested unstressed during heating.

paste-aggregate bond loss at temperatures above 1,000 F (538 C). This bond loss, as evidenced by erosion of mortar during sawing and polishing, probably accounts for the relatively low strengths at temperatures above 900 F (482 C).

Very little change was observed in the physical condition of the sanded lightweight concrete specimens, Fig. 12. The specimen heated to 1,500 F (816 C) developed longitudinal cracks about 3/8 in. (1 cm) from the surface.

SUMMARY

1. Specimens made of the carbonate aggregate concrete or the sanded lightweight concrete (replacement of 60 percent of the fines with sand from Elgin, Ill.) retained more than 75 percent of their original strengths at temperatures up to 1,200 F (649 C) when heated without load and tested hot. The corresponding temperature for the siliceous aggregate concrete was about 800 F (427 C).
2. Strengths of specimens stressed in compression during heating were generally 5 to 25 percent higher than those of companion specimens that were not stressed during heating.
3. Unstressed residual strengths (specimens heated, cooled, and then tested) were somewhat lower than the strengths of companion specimens tested at high temperatures.
4. Strengths of specimens stressed in compression during heating were not significantly affected by the applied stress level, which ranged from 25 to 55 percent of the original strength.
5. Original strength of the concrete had little effect on the percentage of strength retained at test temperature.

These observations are based on results of compressive tests of 3x6-in. (7.5x15-cm) cylindrical specimens performed at various temperatures up to 1,600 F (871 C). Three different concretes, each with two strength levels, were used and three test procedures were followed.

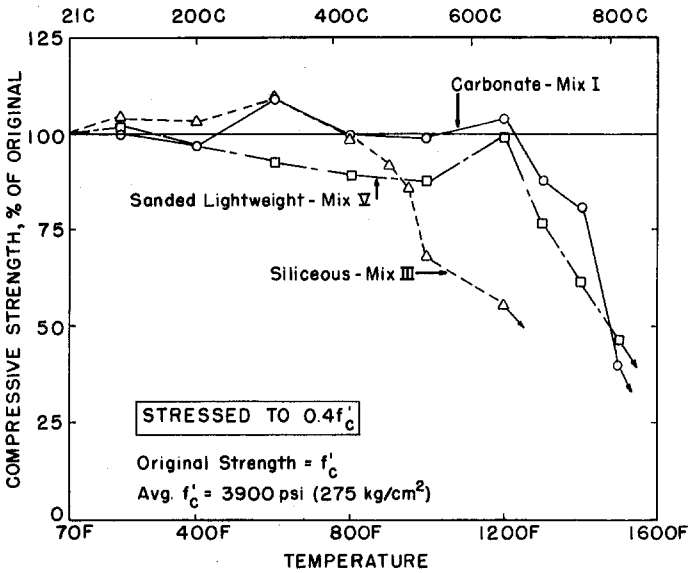


Fig. 8. Effect of aggregate type on the compressive strength of concrete stressed to $0.4f'_c$ during heating.

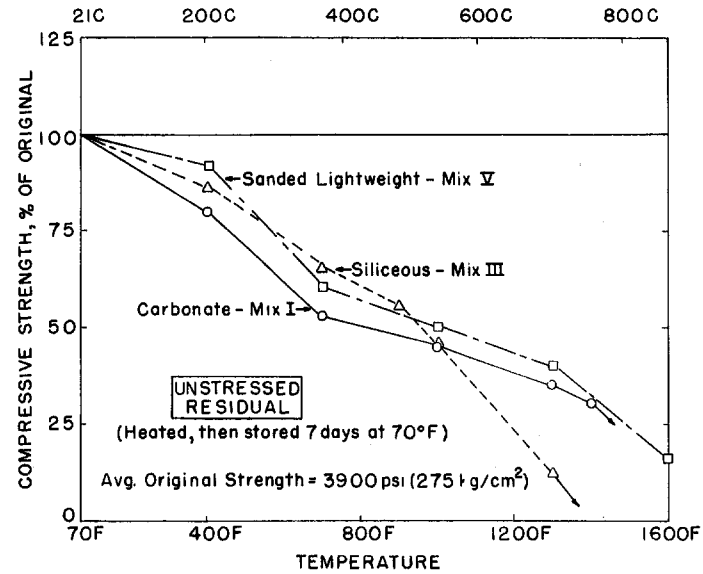


Fig. 9. Effect of aggregate type on the residual compressive strength of concrete.

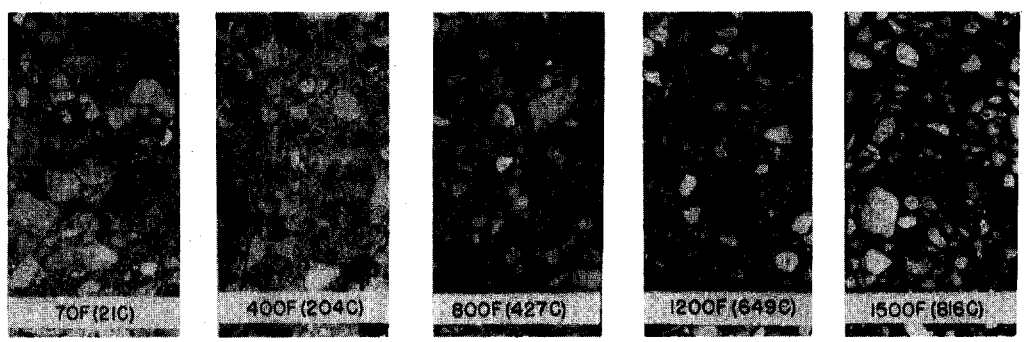


Fig. 10. Sections of 3x6-in. specimens of carbonate aggregate concrete (Mix 1).

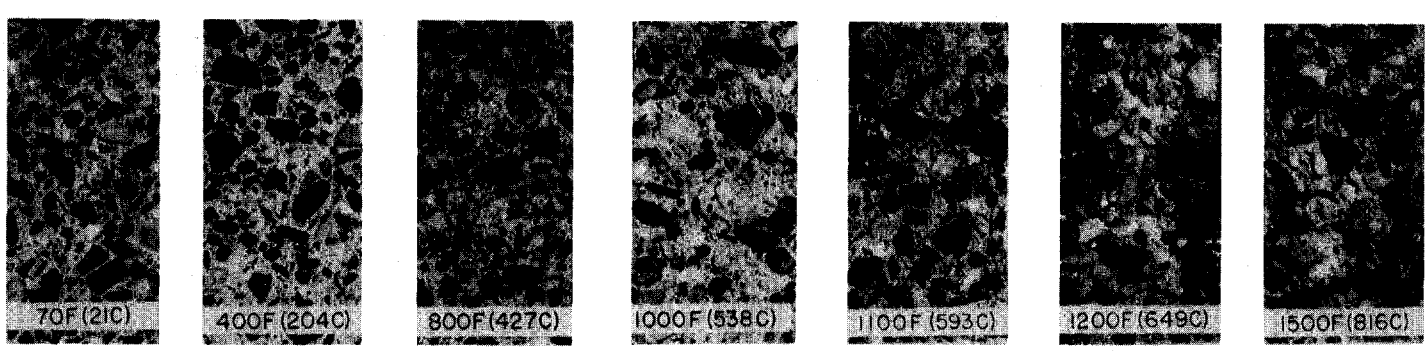


Fig. 11. Sections of 3x6-in. specimens of siliceous aggregate concrete (Mix 3).

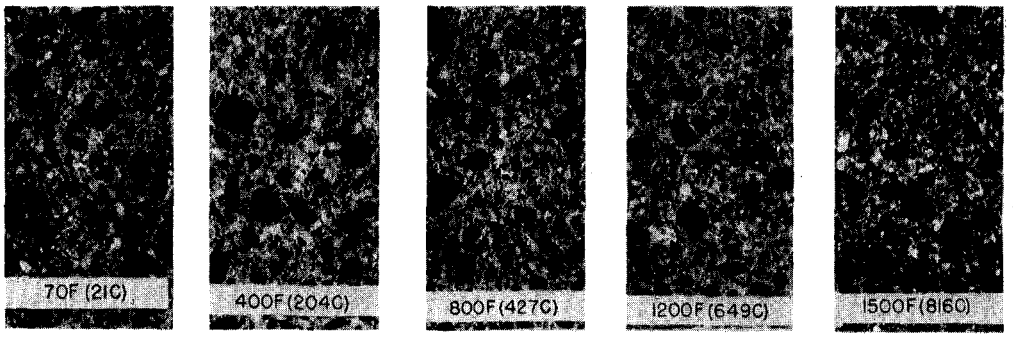


Fig. 12. Sections of 3x6-in. specimens of sanded lightweight concrete (Mix 5).

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APPENDIX. Petrographic Analyses of Aggregates

The following petrographic descriptions of the aggregates used in the tests described in this bulletin were taken from Reference 4.

TABLE A1. Petrography of Sand and Gravel from Elgin, Ill.

Component	Composition of sieve fraction: percent on sieve of size indicated											
Sieve size	3/4 in.	1/2 in.	3/8 in.	1/4 in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	–No. 200
Carbonate	91.1	87.4	87.3	85.6	87.6	80.5	79.6	64.4	46.1	36.4	65.0	92.0
Chert	3.6	4.2	5.2	7.6	6.1	8.9	11.0	–	–	–	–	–
Granite	1.1	1.2	3.5	1.8	2.4	3.6	2.4	–	–	–	–	–
Basalt	2.1	3.0	1.4	2.6	2.6	3.4	2.0	1.2	–	–	–	–
Gabbro	0.3	–	–	0.2	0.5	0.2	0.7	0.3	–	–	–	–
Quartzite	1.8	3.9	1.4	1.3	0.3	3.0	4.3	–	–	–	–	–
Gneiss-schist	–	0.3	1.2	0.9	0.5	0.4	–	–	–	–	–	–
Quartz-chalcedony	–	–	–	–	–	–	–	26.5	45.1	52.5	27.2	4.0
Feldspar	–	–	–	–	–	–	–	7.6	8.8	11.1	6.1	0.5
Misc. igneous and clays	–	–	–	–	–	–	–	–	–	–	1.7	3.5

Particle shape	Percent on sieve			
	3/4 in. - 1/4 in.		No. 4 - No. 200	
	Carbonates	Silicates	Carbonates	Silicates
Rounded	–	–	–	30
Subangular to subrounded	80	100	75	60
Angular	–	–	–	10
Angular to subangular	20	–	25	–

TABLE A2. Petrography of Sand and Gravel from Eau Claire, Wis.

Component	Composition of sieve fraction: percent on sieve of size indicated											
Sieve size	3/4 in.	1/2 in.	3/8 in.	1/4 in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	–No. 200
Granite	37.9	32.9	25.5	31.3	27.0	27.6	12.3	7.4	1.9	4.4	0.6	–
Quartzite	21.6	29.2	34.8	24.6	24.5	20.0	12.3	12.6	10.9	3.1	2.2	–
Quartz	6.3	3.1	4.9	4.8	5.5	18.8	52.2	62.0	73.1	79.5	74.2	92.0
Chert[a]	10.8	7.0	5.2	8.1	9.8	5.9	7.7	3.5	2.0	0.8	2.8	2.0
Sandstone-quartz conglomerate	1.9	0.8	3.1	5.1	5.5	8.3	–	–	–	–	–	–
Rhyolite-dacite	13.9	6.2	2.2	5.1	7.2	4.1	0.8	2.6	1.6	0.8	0.9	–
Feldspar	–	–	–	–	–	–	1.3	5.0	6.6	5.0	10.8	4.0
Diorite	1.9	1.4	3.1	1.8	1.2	–	–	–	–	–	–	–
Graywacke[b]	1.3	9.5	5.8	5.4	4.3	6.5	2.3	1.5	0.3	–	0.6	–
Gneiss-schist	2.5	5.1	10.5	9.3	7.5	4.1	6.4	1.8	0.9	1.1	0.6	–
Basalt	1.9	4.5	4.0	3.9	6.9	3.2	2.6	2.4	0.7	–	0.3	–
Misc. igneous rocks[c] and opaque minerals	–	0.3	0.9	0.6	0.6	1.5	2.1	1.2	2.0	5.3	7.0	2.0

Particle shape	Percent on sieve		
	3/4 in. - 1/4 in.	No. 4 - No. 16	No. 30 - No. 200
Subrounded to rounded	30	20	10
Subrounded to subangular	40	40	40
Angular	30	40	50

[a] "Ironstone," made up of jasper and hematite, is included in the chert classification.
[b] Includes metagraywacke.
[c] The miscellaneous igneous rocks were severely altered and positive identification was impossible. The opaque minerals occurred in the No. 50 and smaller sieve sizes and were largely magnetite.

TABLE A3. Petrography of Expanded Shale from Ottawa, Ill.

Particle shape	Particle surface texture	Microstructural character of air void system	Mineralogy
Coarse aggregate			Mineralogy was similar for all samples examined. The following constituents were present: 50-70 percent glass, Refractive Index = 1.540-1.565 10-30 percent quartz 1-10 percent feldspar 1-10 percent unidentified microcrystaline material Less than 1 percent iron oxides
Tabular to ellipsoidal, subangular to rounded.	Dense. Few voids greater than 1,000 microns diameter were exposed.	Uniform structure with few or no bedding plane separations. Most voids were nearly spherical and isolated, but if connected, showed no directional preference for such connection. Isolated voids were from 5 to 25 microns diameter; a few up to 100 microns. 50-100 micron voids showed some tendency to coalescence. Voids uniformly and closely spaced. Largest voidless area observed was 900 square microns.	
Fine aggregate			
Tabular to ellipsoidal. Progressively more angular with decreasing particle size.	Very dense, smooth. Few voids at surface were larger than 100 microns.	Voids were similar to those described for coarse aggregate. Maximum dimensions of air voids limited by particle size.	

KEYWORDS: aggregates, carbonate aggregates, compressive strength, concretes, expanded shale aggregates, fire resistance, high temperature tests, lightweight aggregate concretes, lightweight aggregates, petrography, plain concrete, research, siliceous aggregates.

ABSTRACT: Compressive strength tests were conducted on 3x6-in. cylindrical specimens heated for short duration to temperatures of 200 to 1,600 F. Variables included aggregate type, test procedure, and original strength of concrete. Carbonate aggregate concrete and lightweight concrete tested hot without prior loading retained about 75 percent of their original strengths at 1,200 F. Specimens heated while loaded had the highest strengths, while strengths of specimens heated, cooled, and then tested were the lowest throughout the temperature range. Original strength of concrete had little effect on the percentage of strength retained at high temperatures.

REFERENCE: Abrams, M. S., *Compressive Strength of Concrete at Temperatures to 1,600 F* (RD016.01T), Portland Cement Association, 1973. Authorized reprint from copyrighted American Concrete Institute Special Publication SP-25.

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