CANADA

EFFECT OF HIGH TEMPERATURES ON CONCRETES INCORPORATING DIFFERENT AGGREGATES

by

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MINERAL PROCESSING DIVISION

DEPARTMENT OF MINES AND TECHNICAL SURVEYS, OTTAWA

MINES BRANCH
RESEARCH REPORT

R 64

PRICE 25 CENTS

MAY 1960

Mines Branch Research Report R 64

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SYNOPSIS

Changes in physical properties of concrete beams and cylinders made with gravel, sandstone, limestone and expanded slag aggregates were studied after exposure to various temperatures ranging from 100 to 800°C.

Results indicated that the residual compressive strength of concrete increased up to 10% when the specimens were heated up to 300°C, whereas the flexural strength decreased 34% with limestone and 55% with gravel aggregate. After 500°C exposure, losses in strength of corresponding concretes were 19 to 24% in compression and 58 to 80% in flexure.

In temperatures over 500°C the residual strength of all types of concrete decreased sharply due to dehydration of chemical constituents in the cement paste.

Results from the four types of concrete investigated indicate that limestone concrete gave the best performance up to 700°C, at which temperature decomposition of carbonates on the surface of test specimens was observed.

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Note: A condensed version of this report was presented as a paper at the Annual Meeting of the American Society for Testing Materials, Atlantic City, N. J., on June 30, 1960.

Direction des Mines
Rapport de recherches n° R 64

COMPORTEMENT DE BÉTONS FAITS DE DIFFÉRENTS AGRÉGATS ET SOUMIS À DES TEMPÉRATURES ÉLEVÉES

par

N.G. Zoldners*

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RÉSUMÉ

Après les avoir soumis à diverses températures allant de 100 à 800° C, on a étudié les changements qui se sont produits dans les propriétés physiques de poutres et de cylindres de béton faits de gravier, de grès, de calcaire et de laitier expansé.

Les résultats ont indiqué que la résistance résiduelle du béton à la compression augmente parfois jusqu'à 10 p. 100 après chauffage des échantillons jusqu'à 300° C, tandis que la résistance à la flexion diminue de 34 p. 100 si l'agrégat est du calcaire, et de 55 p. 100 si c'est du gravier. Après chauffage à 500° C des bétons correspondants, les diminutions de résistance à la compression s'établissent entre 19 et 24p. 100, et entre 58 et 80 p. 100, en ce qui concerne la résistance à la flexion.

A des températures supérieures à 500° C, la résistance résiduelle de tous les bétons décroît de façon marquée du fait de la déshydratation des constituants chimiques de la pâte de ciment.

Les résultats des expériences effectuées sur ces quatre types de béton indiquent que le béton au calcaire est celui qui se comporte le mieux jusqu'à 700° C; à cette température, on constate que les carbonates se décomposent à la surface des échantillons étudiés.

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Note: Un résumé du présent rapport a fait l'objet d'une communication présentée à la réunion annuelle de l'American Society for Testing Materials, à Atlantic City (N.J.), le 30 juin 1960.

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INTRODUCTION

Concrete is recognized as an excellent fire-resistive building material.

Building codes specify the fire protection requirements for specific structural members in terms of fire resistance ratings based upon tests made in accordance with ASTM standards. Different structural assemblies have been fire-tested and given hourly ratings in a fire-retardant classification.(1)*

Over the years, accumulated experience obtained from fire-endurance and heat-transmission tests on structural assemblies has provided sufficient data for fire protection, but little research has been done on the behaviour of concrete subjected to high temperatures.

With the present-day uses of concrete in certain building construction and industrial installations, and in turbo-jet runways, atomic reactors and missile launching pads, additional information is required on the effect of high temperatures.

Basic research on physical properties under varying thermal conditions could provide this information.

Fundamental research studies of the fire resistance of concrete have been started recently at the new Fire Research Laboratories of the Portland Cement Association.(2, 3)

*The numbers in parentheses refer to the list of references on page 36.

An investigation on concrete properties in the lower temperature ranges has been conducted at the University of Wisconsin.[4]

Research work in this field was begun at the Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada, early in 1958.

A list of references and related publications is included at the end of this paper.

SCOPE OF RESEARCH

Primarily, this project was undertaken to study the effect of high temperatures on concrete prepared with different aggregates. No attempt was made to evaluate the performance of concrete structural members in fire exposures.

Evaluation of fired concrete specimens by determining the compressive strength only is misleading. Multiple methods of evaluating the physical conditions of concrete were applied in this project.

Flexural and compressive strengths of beams and cylinders, along with changes of weight, volume and ultrasonic pulse velocities, were studied and ruptured concrete surfaces were microscopically examined, to determine the degree of concrete deterioration after exposure at elevated temperatures between 100 and 800°C.

Thermal conductivity values and specific heat data on each of the four types of concrete were used to compare the thermal properties of the materials.

It is hoped that information obtained in this investigation may contribute to the knowledge of concrete and its fire resistance properties.

MATERIALS

Cement

A Type 1 portland cement of Canadian manufacture was used in this project. The chemical analysis and the compound composition of this cement are shown in Table 1.

TABLE 1

Chemical Analysis and Compound Composition of Cement*

Chemical Analysis		Compound Composition	
	%		%
SiO_2	21.05		
Al_2O_3	5.66	C_3S	47.1
Fe_2O_3	3.03	C_2S	24.9
CaO, Combined	62.22	C_3A	9.9
CaO, Free	0.83	C_4AF	9.2
MgO	2.75	$CaSO_4$	4.2
SO_3	2.47	MgO)	
Na_2O	0.48	Ignition Loss)	4.6
K_2O	0.56	Alkalies)	
Ignition Loss	0.81		
Total	99.86	Total	99.9

* Chemical analysis by Canada Cement Company Limited, Hull, Quebec.

Aggregates

Identically-graded fine and coarse aggregates were prepared from the same material - gravel, sandstone, limestone, and expanded slag.

(1) Gravel was from an operating pit of a glacial-fluvial deposit at Shawville, Quebec. This gravel, a heterogeneous mixture, is being used in ready-mixed concrete in Ottawa, Ontario.

(2) Sandstone was from a quarry in Potsdam formation at Beauharnois, Quebec. The rock is clean, white, and well indurated.

(3) Limestone was obtained from an Ottawa quarry. The rock is a dark, fine-grained, high-calcium variety of limestone, typical of parts of the local Trenton formation.

(4) Expanded slag, a commercial by-product of the steel industry, was obtained from Hamilton, Ontario.

A detailed petrographic study was made on each of the four types of aggregate used in the concrete to be tested. When necessary, X-ray diffraction and chemical analyses were carried out. Table 2 summarizes the results of these studies.

Gravel, sandstone and limestone aggregates were crushed and screened into size fractions, and then recombined according to the grading shown in Table 3 under the columns marked "Standard".

Expanded slag coarse aggregate was used as received, whereas fine aggregate was recombined as shown in Table 3.

TABLE 2

Petrography of Aggregates Used in Concrete

Aggregate	Percentage	Description
Gravel		Heterogeneous aggregate of gneissic, schistose, granitic, and mafic igneous or metamorphic rock material with lesser amounts of sedimentary limestone and sandstone, typical of many glacial-fluvial deposits.
1. Metamorphic rock (gneiss, schist, minor calcite)	45%	
2. Granitic and minor basic igneous rock	42%	
3. Limestone and clayey limestone	12%	
4. Sandstone	1%	
Sandstone		Relatively pure, white sandstone or orthoquartzite, consisting of firmly cemented fine, equant, rounded quartz grains. 12% is buff-weathering.
1. White to bluish	88%	
2. White, buff streaks	12%	
Limestone		Fairly pure high-calcium, fine-grained limestone containing a few fossils. Shaly portions contain dispersed clay.
1. High-calcium, hard	80%	
2. Shaly (15% clay)	20%	
Expanded Slag		Two phases: (1) Grey-white, relatively dense, containing akermanite and monticellite. (2) Buff, porous, containing merwinite.
1. Grey-white	58%	
2. Buff, porous	42%	

TABLE 3

Grading of Aggregates

Coarse Aggregate			Fine Aggregate		
Sieve No.	Percentage Passing		Sieve No.	Percentage Passing	
	Standard	Exp. Slag		Standard	Exp. Slag
3/4 in.	100.0		4 mesh	100.0	100.0
1/2 in.	56.0		8 "	90.0	80.0
3/8in.	37.5	100.0	16 "	67.5	55.0
No.4 mesh	0.0	0.0	30 "	42.5	35.0
			50 "	20.0	20.0
			100 "	6.0	10.0

Some physical properties of the four aggregates, and the proportions of coarse to fine aggregate in the concrete mixes, are shown in Table 4.

TABLE 4

Physical Properties and Mix Proportions

	Gravel		Sandstone		Limestone		Exp. Slag	
	C.A.	F.A.	C.A.	F.A.	C.A.	F.A.	C.A.	F.A.
1. Specific Gravity (bulk, SSD base)	2.71	2.70	2.62	2.60	2.68	2.66	1.76	2.02
2. Absorption % (by weight)	0.78	1.22	1.1	1.5	0.92	1.22	18.9	20.0
3. Mix Proportions (by weight, %)	59	41	52	48	52	48	25	75

Abbreviations: C.A. - Coarse aggregate
F.A. - Fine aggregate
SSD - Saturated, surface-dry

PREPARATION OF TEST SPECIMENS

Concrete Mixes

All concrete mixes were prepared with the same cement factor, 480 lb of cement per cubic yard of concrete.

All but one of the mixes were non-air-entrained with a consistency of 2 to 2 1/2 in. slump. In mixes with expanded slag aggregate, an air-entraining admixture was added for workability.

Mix proportions and other data are shown in Table 5.

Test Specimens

Ten 1.6 cu ft batches were prepared for each of the four types of concretes.

Normally, from each batch either twelve beams (3 1/2 x 4 x 16 in.), or eighteen cylinders (4 x 8 in.), or two slabs (3 x 13 x 17 1/2 in.) were moulded.

From every batch, two sets of fire-test specimens and one set of reference specimens were selected. A set of fire-test specimens consisted of either four beams or six cylinders. A reference set consisted of either four beams or three cylinders.

The first batch was used to prepare beam and cylinder specimens for preliminary firings and for standard test specimens.

From the last batch, two slabs were prepared for thermal conductivity, and twelve spare test cylinders were made from the remaining material.

TABLE 5

Concrete Mix Proportions

Type of Concrete Aggregate	Average Mix Proportions per 1 cu yd					Mix Characteristics			
	Cement, lb	SSD Aggreg. Fine, lb	SSD Aggreg. Coarse, lb	Water, lb	Admixt.	W/C ratio	Slump, in.	Air, %	Unit Wt., lb/cu ft
GRAVEL	480	1345 41%	1935 59%	300	nil	0.62	2 1/2	1.5	150.5
LIMESTONE	480	1550 48%	1670 52%	314	nil	0.65	2 1/2	1.1	148.8
SANDSTONE	480	1450 48%	1570 52%	330	nil	0.69	2	2.9	141.0
EXPANDED SLAG	480	1357	452	475	Darex 6 oz	-	0	9.0	102.5

Table 6 shows a breakdown of all test specimens for one type of concrete, as prepared from each batch.

TABLE 6

Summary of Test Specimens
(For one test series only)

Number of Mix Batches	Type of Test Specimens	Number per Batch	Allocation of Specimens					Total No. Spec.
			Fire Tests	Refer. Spec.	Stand. Spec.	Contr. Spec.	Therm. Cond.	
1	Beams	6	3	-	-	3	-	6
	Cylinders	12	-	-	12	-	-	12
4	Beams	12	8	4	-	-	-	48
4	Cylinders	18	12	3	-	3	-	72
1	Slabs	2	-	-	-	-	2	2
	Cylinders	12	12	-	-	-	-	12
			Total number of specimens:					152

This schedule allowed eight test firings to be made at eight different temperatures, using a set of four beams or six test cylinders for each firing. A sufficient number of specimens were available to conduct two preliminary firings for each series, in order to establish the proper heat control in the furnace.

On the 4-in. sides of the beams two stainless steel plugs were cast 10 in. apart, to provide reference points for length measurements.

Curing Test Specimens

The twelve test cylinders from the first batch were stored under standard moist-curing conditions for 7-day, 14-day, 28-day and 12-month compression tests.

All other test specimens, after 7-day initial standard moist-curing, were kept in a dry-storage room for one year until tested.

Three test cylinders and three beams from the four series were selected as control specimens for density and moisture-change determinations in the dry-storage room. These specimens were weighed regularly once a week, providing a moisture-loss record.

Properties of Hardened Concrete

Density values at the beginning and at the end of the 12-months room-drying period, as well as the amounts of moisture lost and moisture remaining in the room-dried control test specimens, are shown in Table 7. Also shown are compressive strengths of standard moist-cured and of room-dried concrete test specimens. The values are the average of three results obtained for each set of beams or cylinders.

HIGH-TEMPERATURE EXPOSURE

Fire-Test Installations

A gas-fired furnace of 10 cu ft capacity was used for the firing tests. Three exchangeable gas burners on each side of the furnace, coupled with air valves and draft regulators, provided temperature control in the heating chamber.

Two thermocouples, one in the middle of the chamber and the other between test specimens, were connected to an automatic temperature recorder to provide a continuous record of the furnace temperature.

TABLE 7

Properties of Hardened Concrete

Type of Concrete Aggregate	Standard Moist-Cured Specimens					12 Month Room-Dried Control Test Specimens					
	SSD 7 d Density, lb/cu ft	Average Compressive Strength of 4 x 8 in. Test Cylinders				Room-Dry 4 x 8 in. Cylinders		3 1/2 x 4 x 16 in. Test Beams			
		7 d psi	14 d psi	28 d psi	12 mo psi	Density, lb/cu ft	Comp. Str., psi	Loss in Weight, %	Free Moist. Retained, %	Mod. of Rupture, psi	Beam End Comp. Str., psi
GRAVEL	151.6	2340 67%	3110 89%	3475 100%	4517 130%	143.9	4008	5.1	0.5	763 14.6%	5288 100%
LIMESTONE	150.0	2719 68%	3465 87%	4003 100%	4810 120%	142.8	4160	4.9	0.5	719 15.4%	4667 100%
SANDSTONE	144.4	1900 68%	2315 83%	2772 100%	4080 147%	136.9	3542	5.2	0.4	588 13.9%	4247 100%
EXPAND. SLAG	111.2	934 64%	1175 80%	1461 100%	Not Tested	96.5	1597	13.2	0.8	397 19.9%	1998 100%

A vertical section of the furnace is shown in Appendix 1, on page 38. The dimensions of the furnace chamber were: width, 20 in.; depth, 42 in.; and height at the crown, 24 in.

Thermal Distribution

To determine the heat distribution in the furnace and the penetration within test specimens, a preliminary firing was conducted. Six chromel-alumel thermocouples were used with a potentiometer. Four of the thermocouples were installed to measure thermal differentials between the outside and the inside of a beam and of a cylinder, one was placed between test samples, and one indicated the temperature in the middle of the furnace.

Data obtained from the preliminary firing were sufficient to establish two time-temperature curves for a concrete test beam, one representing the temperature rise on the surface and the other the temperature rise in the centre, showing the heat penetration. (See Appendix 2, on page 39.) These curves indicate that the temperature rise within the test specimen lagged behind the furnace temperature rise by about half an hour. When the furnace reached the pre-determined temperature, one hour of heat-soaking was specified for the test specimens to reach thermal equilibrium.

In a trial run with two thermocouples located as shown in Appendix 1, a temperature of 1000°C was recorded by the lower thermocouple in about two hours' time. The recorded curves obtained indicated that the temperature rise in the furnace followed closely the standard time-temperature curve as specified by

ASTM E 119-58. (See Appendix 3.)

Fire-Test Procedure

The heating chamber of the gas furnace provided space for either 12 cylinders (4 x 8 in.) or 4 beams (3 1/2 x 4 x 16 in.) at one time.

Cylinders were placed in groups of three in four rows, with top ends protected from the direct flame by refractory brick. Six cylinders from each of two concrete test series were fired at the same time.

Beams were placed horizontally on their 3 1/2 in. sides (see Appendix 1), with the steel reference plugs located on both 4 in. sides. All four beams were from the same concrete batch.

Fire-test specimens were exposed from room temperature to 100°, 150°, 200°C, and then by 100-degree increments for each firing, up to 800°C. After reaching the predetermined end temperature, specimens were heat-soaked for one hour.

Some typical temperature records for different firing ranges, provided by the two thermocouples, are shown in Appendix 4.

The lowest temperature was given by the bottom thermocouple, which recorded temperatures that were from 100 to 300 degrees lower than the upper one. The bottom temperature was the nominal temperature of the test environment and was held constant at the predetermined value. The upper temperature decreased gradually, approaching equilibrium at the end of the heat-soaking period.

Immediately after firing, three of the six test cylinders of each series were removed from the furnace, quenched in water for 5 minutes, and then transferred to a drying oven at 50°C for 18 hours. The remaining cylinders were left overnight in the closed furnace to cool slowly. The next morning all fired specimens were placed in a desiccator to bring them in four hours to room temperature and hold until tested. The beam specimens were not quenched.

PHYSICAL TEST PROCEDURES AND METHODS

Physical Tests

To evaluate the effect of high temperatures on concrete, the following investigations were carried out:

(1) Weight determinations.

(2) Length measurements.

(3) Pulse velocity determinations.

(4) Flexural and compressive tests on beams.

(5) Compression tests on cylinders.

(6) Tests of thermal properties of concretes.

(7) Petrographic examinations of the heated and crushed test specimens.

The fire-test specimens were weighed, and the length and pulse velocity of beams measured, before and after heat exposure.

All fire-test specimens had been preconditioned by air-drying for a period of twelve months.

Methods

Test specimens were weighed with a probable accuracy of $\pm$0.001 lb (0.5 g).

Length measurements were made on beam specimens only. Reference points were drilled in the embedded stainless steel plugs 10 in. apart. A Whittemore strain gauge was used, having a dial reading of one ten-thousandth inch per inch.

The ultrasonic pulse velocities were determined by an electronic concrete tester, type UCT, made by A. E. Cawkell, England. This instrument operates at a 100 Kc/s frequency with a one-tenth microsecond sensitivity.

Concrete flexural strength was tested on the 3 1/2 x 4 x 16 in. beams according to ASTM Standard Method C 78-57, using simple beam, third-point loading. Specimens were tested in a Tinius Olsen Super "L" compression testing machine, the sensitivity of which, in the 1200-lb range, was 2 lb per dial division.

Portions of beams broken in flexure were tested for compression according to ASTM Standard Method C 116-49, the modified cube method.

Concrete cylinders were tested for compressive strength according to ASTM Standard Method C 39-56T. For all compression tests, an Amsler compression testing machine of 600,000-lb capacity, with a pendulum dynamometer, was used.

To compare thermal properties of concretes prepared with different types of aggregates, the following tests were carried out:

(1) Thermal conductivity was determined on 3 x 13 x 1/2 in. concrete slabs, in accordance with ASTM Standard Method C 202-47.

(2) Specific heat values of 1 1/2 x 1 1/2 x 4 in. concrete specimens were determined by the "Method of Mixtures", (a standard procedure in physics) in a calorimeter using water.

PHYSICAL TEST RESULTS

Test results on concrete after exposure to various elevated temperatures are shown in Table 8. They are based on average values from tests on either three cylinders or four beam specimens.

Pulse velocity of specimens after firing is shown as a percen- of that before firing. No measurements of pulse velocity were made on concrete beams prepared with expanded slag aggregate, because specimen surface porosity caused inconsistency in the test results.

Fired flexural and compressive strengths of test specimens are shown as a percentage of the strength values of companion reference specimens.

Weight loss of the room-dried specimens, after heat exposure, is shown in Table 9 as a percentage of the weight before exposure. The same table shows the permanent length changes, both drying shrinkage and dilation, of concrete specimens determined by direct measurements in units of thousands of an inch per inch. Each figure shown in Table 9 is based on the average value obtained in tests on sets of four beams each.

TABLE 8

Test Results on Concrete After Exposure to High Temperatures

Exposure Temperature °C	Ultrasonic Pulse Velocity, %				Fired Strength in Per Cent of Original Average Strength											
					Beam Flexural Strength,				Beam Ends Comp. Strength,				Cylinder Comp. Strength,			
	Gr	Sa	Ls	Sl	Gr	Sa	Ls	Sl	Gr	Sa	Ls	Sl	Gr	Sa	Ls	Sl
20	100	100	100	-	100	100	100	100	100	100	100	100	100	100	100	100
100	99	99	-	-	83	93	-	-	93	99	-	-	100	-	-	-
150	96	98	98	-	68	85	85	-	92	91	95	-	97	102	95	-
200	88	94	96	-	63	75	73	68	97	96	91	99	99	112	98	105
300	74	82	92	-	45	55	66	34	102	107	110	84	103	97	94	77
400	69	65	85	-	26	35	62	16	82	80	91	64	85	84	94	73
500	47	54	69	-	20	26	42	18	71	75	89	65	76	71	81	67
600	38	29	54	-	19	12	29	16	67	49	66	68	46	43	52	71
700	30	24	46	-	12	8	18	14	33	35	46	62	26	30	42	49
800	-	-	-	-	-	-	-	14	-	-	-	28	15	21	24	30

Notes: (1) Aggregate types used in concrete are marked by abbreviations: Gr - gravel, Sa - sandstone, Ls - limestone, Sl - expanded slag.

(2) No ultrasonic pulse velocity determinations were made on exp. slag concrete.

(3) Test results are shown as a percentage of values obtained on reference specimens at room temperature (20°C).

TABLE 9

Length and Weight Changes of Concrete After Fire Exposure

Exposure Temperature °C	Weight Loss of Room-Dry Concrete in %				Permanent Length Changes of Concrete Beams After Exposure Measured in 10^{-3} in./in.			
	Gr	Sa	Ls	Sl	Gr	Sa	Ls	Sl
100	0.04	0.06	0.05	-	-0.01	-0.02	-	-
150	0.30	0.30	0.30	-	-0.01	-0.03	-	-
200	1.17	1.14	1.16	1.80	-0.03	-0.10	-0.05	0.19
300	1.86	1.70	1.80	3.07	+0.02	-0.11	-0.13	-0.32
400	2.14	1.90	1.97	4.07	+0.5	+0.2	+0.3	-0.27
500	2.60	2.19	2.48	4.50	+2.2	+1.0	+1.1	-0.40
600	3.42	2.94	3.20	4.95	+4.2	+5.0	+3.1	-0.34
700	4.61	3.23	4.6	5.77	+6.0	+8.8	+5.1	-0.26

Abbreviations: Gr - gravel, Sa - sandstone, Ls- limestone, Sl - expanded slag, for aggregate types used in concrete samples.

Thermal conductivity and specific heat values for four types of concrete, shown in Table 10, were obtained in laboratory tests. The values of heat diffusivity were calculated, using the equation:

$$h^2 = K/Cd \qquad \text{...............(5)}$$

where:

h^2 = heat diffusivity of concrete, square feet per hour;

K = coefficient of thermal conductivity, B.t.u. per square foot per hour per degree F for 1 in. thickness of material;

C = specific heat value for concrete, B.t.u. per pound per degree F;

d = bulk density of the room-dry concrete, pounds per cubic foot.

The physical features of heat-exposed and crushed concrete test cylinders are shown in Table 11. Stereomicroscopic examination of the cylinders included studies of aggregate-mortar bond, ruptured particles, and aggregate and cement paste, after exposure to elevated temperatures. Photographs in Appendix 5 illustrate damages sustained by concrete test specimens clowly cooled or quenched after exposure to temperatures of 700 and 800°C.

TABLE 10

Thermal Properties of Concrete

Type of Concrete Aggregate	Thermal Conductivity			Room-Dry Concrete Density, lb/cu ft	Mean Specif. Heat 25 to 400°C, Btu/lb/°F	Heat Diffusivity, ft^2/hr
	Mean Temp.		Coeff. K $\frac{\text{Btu x in.}}{\text{°F x ft}^2\text{ x hr}}$			
	°C	°F				
GRAVEL	100	212	10.60			0.032
	164	327	10.60	143.9	0.229	
	402	756	8.95			0.027
LIMESTONE	164	327	6.75	142.8	0.236	0.020
	394	740	8.04			0.024
SANDSTONE	95	202	15.80			0.050
	169	336	15.75	136.9	0.233	
	406	763	10.64			0.033
EXPAND. SLAG	182	359	3.51	96.5	0.222	0.016
	398	749	3.45			

TABLE 11

Physical Features of Heat-Exposed Crushed Concrete Cylinders and Beams

Aggregate	Temperatures	Aggregate-Mortar Bond	Ruptured Surface	Conclusions
(1) Gravel	200° to 400°C	Strong; few boundary cracks.	2-5% across small* agg. particles, least at 400°C.	Start of bond yield at 400°C; some agg. may be expanding.
	500°, 600°C	Weakened. Yielding along agg. surfaces; fine mortar cracks.	1-2% across particles less than 3/8 inch. Quench 600°C; outer rim separating.	Cement decomposes. Some agg. particles expanding.
	700°, 800°C (See Plates 1 and 2 shown in Appendix 5)	Poor. Agg. particles loose, concrete exfoliating.	1-2% across friable particles. Powdery cement. Micaceous particle pop-outs.	Mortar bond destroyed by heat. Pop-outs from expanding particles.
(2) Limestone	200° to 400°C	Strong; few boundary cracks.	5-10% across small aggregate.	Heating: No visible effect.
	500°, 600°C	Weakened. Yielding along agg. surfaces; fine mortar cracks.	5% across small aggregate at 500°C. Less than 1% at 600° quenched.	Heating decomposes cement. Quench: Fine cracks at 600°C.
	700°, 800°C (See Plates 3 and 4 shown in Appendix 5)	Weak; abundant cracks; powdery cement; limestone decomposing.	1-5% across small aggregate. Cyl. expanding, cracking on outside.	Heating decomposed cement. Limestone starting to decompose at 700°C.
(3) Sandstone	150° to 500°C	Strong. Quenching at 500° yields fine mortar cracks.	5% across small aggregate.	Heating: No visible effect. Quench: Fine cracks at 500°C.
	600°, 700°, 800°C (See Plate 5 shown in Appendix 5)	Weakened. Agg. clean on surface; fine mortar cracks.	2-5% across weaker particles. 700°C: Expanded, cracked cylinders.	Heating breaks down cement. Note: Quartz $\alpha \rightarrow \beta$ at 573° weakens.
(4) Expanded Slag	200° to 600°C	Strong. Contact cracks, clean surfaces at 600°C (weakened).	15 - 20% across small aggreg. Follows large agg. surfaces.	Heating: No visible effect. Quench: Fine cracks at 600°C.
	700°, 800°C (See Plate 6 shown in Appendix 5)	Weakened, cracking along grain boundaries.	5% across small aggregate. Inter-agg. cracks, powdery cement.	Heating decomposes cement.

*Note: 'small' aggregate refers to particles 1/4 - 1/2 inch in diameter.

DISCUSSION OF RESULTS

Results compiled in Table 8 are plotted separately for each type of aggregate in Figs. 1 to 4 (see page 23).

Changes in pulse velocity and flexural strength are both represented by smoothly declining curves.

Graphs for beam-end compressive strength differ from flexural strength graphs. They show strength increases after heating to 200 or 300°C. With further temperature rise, the compressive strength decreases, but to a much lesser degree than does the flexural strength.

Gravel and sandstone concretes, after exposure at 500°C, show residual compressive strengths of 71 and 75 per cent respectively of the original, whereas flexural strengths have dropped to 20 and 26 per cent respectively. Limestone concrete performs better, showing in compression 89, and in flexure 42, per cent residual strengths. Expanded slag concrete shows a rapid loss of flexural strength upon heating. It stands up well in compression, showing a sudden loss only after 700°C exposure.

Figures 5 to 8 (see page 24) show graphically the compressive strength of test cylinders.

The solid-line graphs were plotted from the last column in Table 8 and represent the slowly-cooled test cylinders. They

FIG.1 — CONCRETE BEAMS AFTER FIRE EXPOSURE

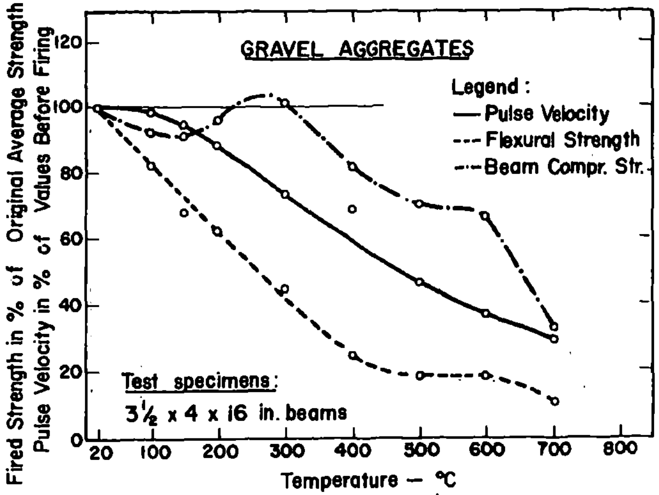


FIG.2 — CONCRETE BEAMS AFTER FIRE EXPOSURE

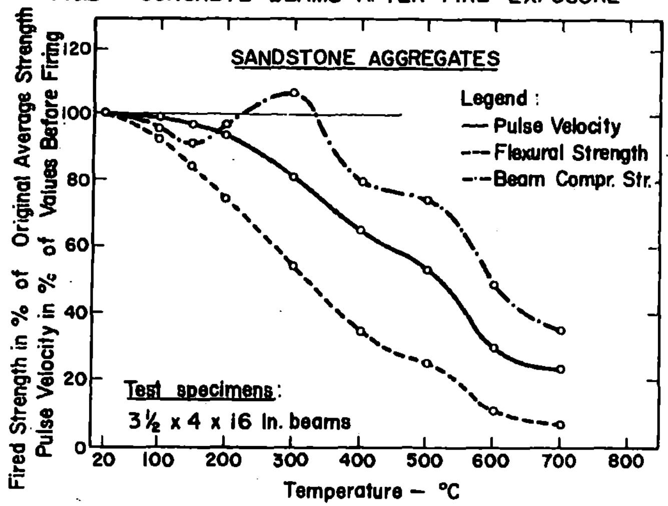


FIG.3 — CONCRETE BEAMS AFTER FIRE EXPOSURE

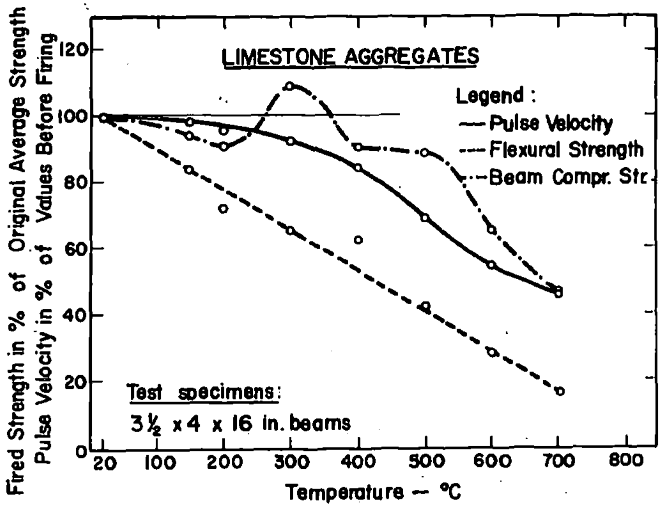


FIG.4 — CONCRETE BEAMS AFTER FIRE EXPOSURE

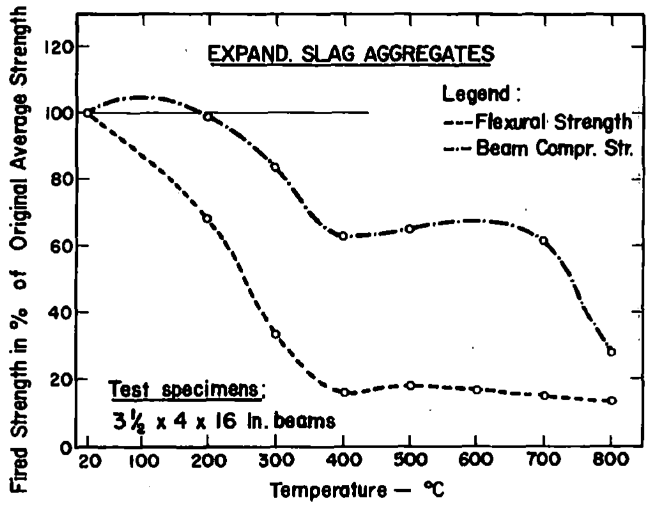


FIG.5 — CONCRETE CYLINDERS AFTER FIRE EXPOSURE

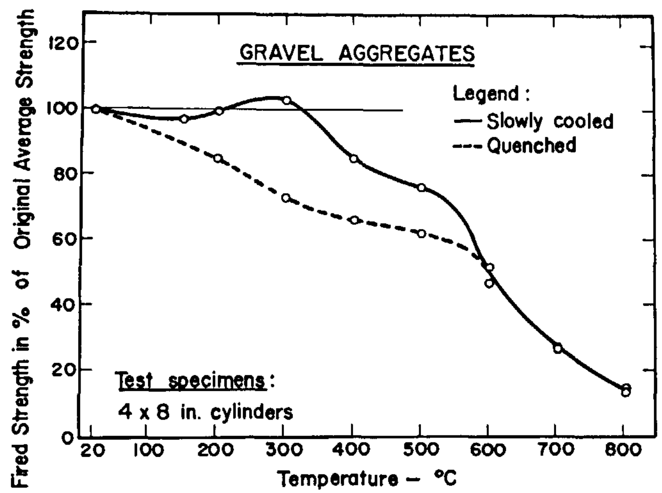


FIG.6 — CONCRETE CYLINDERS AFTER FIRE EXPOSURE

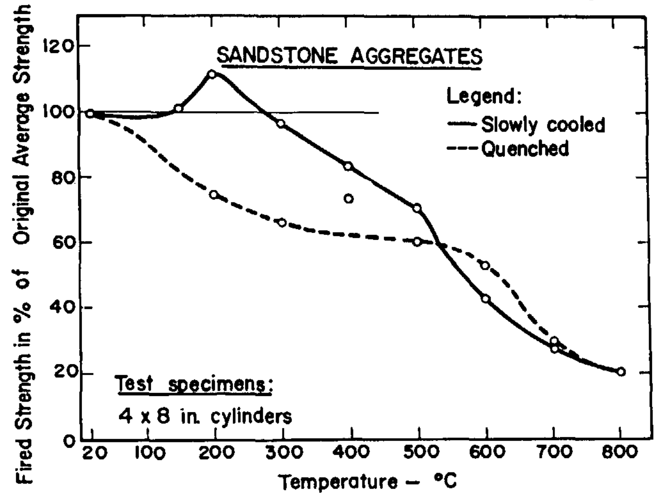


FIG.7 — CONCRETE CYLINDERS AFTER FIRE EXPOSURE

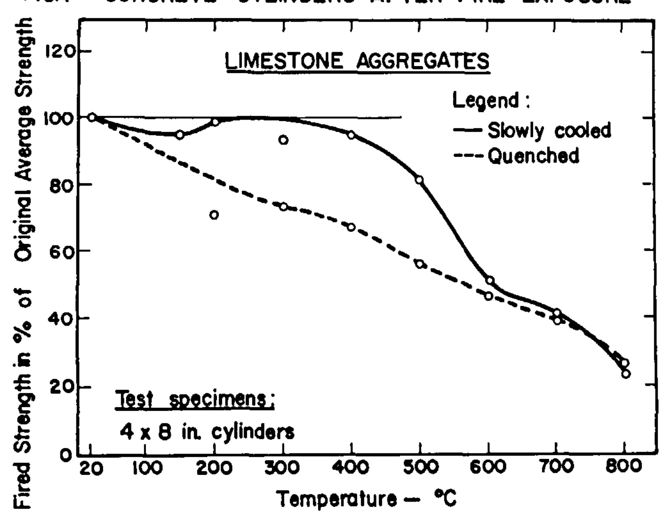
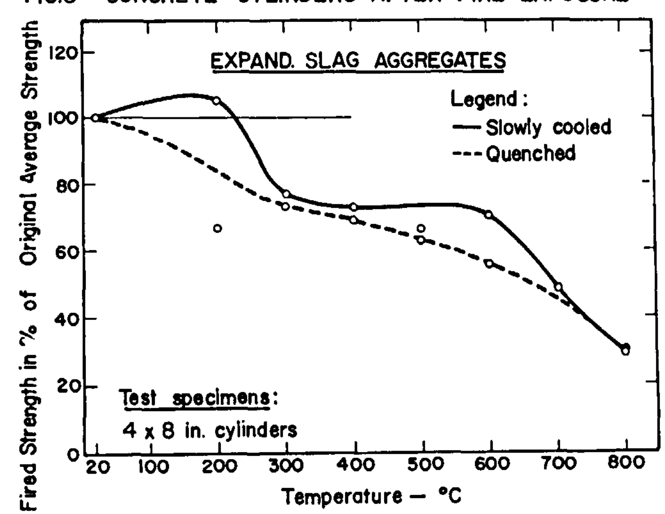


FIG.8 — CONCRETE CYLINDERS AFTER FIRE EXPOSURE



closely resemble the corresponding curves of the beam-end compression tests.

The dashed-line graphs represent compressive strength of water-cooled, or quenched, test cylinders. The much lower strength of these test specimens must be attributed to the destructive effect of thermal shock produced by quenching.

The significant drop in strength of the slowly-cooled concrete cylinders, after exposure to temperatures above 500°C, is not evident from the tests with quenched cylinders. When broken, the quenched cylinders showed an outer shell of harder, discoloured concrete. This shell probably was produced by rehydration of cement by water which penetrated the cylinders during quenching.

From the test results it appears that quenching in water partly restored concrete strength that had been lost by dehydration of portland cement paste at elevated temperatures. (See Plate 3-B, shown in Appendix 5.)

The curves in Figure 9, showing permanent length changes and weight losses, were plotted from test data compiled in Table 9. Separate curves show weight losses and shrinkage or expansion of concrete specimens made with gravel, sandstone, limestone and expanded slag aggregates, after exposing the concrete to elevated temperatures.

Loss of weight of concrete during heating appears to take place in three stages, as follows:

(1) Drying - evaporation of free moisture by heating from 100 to 400°C.

(2) Dehydration - loss of non-evaporable water, or the water of hydration, by heating from 400 to 600°C. [13]

(3) Decomposition - dissociation of calcareous aggregates by release of carbon dioxide in limestone concrete exposed to temperatures over 700°C.

The permanent length changes of concrete samples after heat exposure resulted from complex physical and chemical changes involving cement paste and/or aggregates.

In the lower temperature ranges these changes resulted in a shrinkage, but after reaching a temperature above 300°C they resulted in a net expansion. A rapid expansion of gravel concrete observed at 400°C was about twice the expansion of limestone concrete. At this temperature the flexural strength of gravel concrete specimens had dropped to 26 per cent of the original. Sandstone concrete showed sudden expansion after exposure to temperatures above 500°C.

Shrinkage of cement paste, caused by drying of concrete, counteracts thermal expansion. When concrete drying is completed, expansion progresses more rapidly, at a rate dependent on the thermal expansion characteristics of the rock type used for aggregate. [3]

Concrete made with expanded slag aggregate showed no permanent expansion after heat exposure. A residual shrinkage of 0.03% was observed upon heating to 300°C.

Curves in Figure 10, plotted from test data compiled in Table 8, show losses in flexural strength of concrete made with four different types of aggregates. According to this graph, the limestone concrete performed best. In the lower temperature range, sandstone concrete had greater strength than other concretes, but failed at 530°C. Gravel concrete reached a low strength at 450°C, which coincided with the rapid expansion of concrete (Figure 9) and with a drop in thermal conductivity (Table 10). The rapid loss in flexural strength of expanded slag concrete between 200 and 400°C may be explained by its higher drying shrinkage, which reached its maximum at 300°C (Figure 9).

Curves in Figure 11, plotted from test data compiled in Table 8, show changes in ultrasonic pulse velocity on three types of concrete after exposure to various high temperatures.

By means of pulse velocity measurements the smallest cracks (microcracks) in the cement paste structure can be detected. Such minor internal defects would not affect the compressive strength, but would be reflected immediately in the flexural strength of concrete.

Changes in ultrasonic pulse velocity reflect changes in structural properties of concrete and its modulus of elasticity.[6] The dynamic Modulus of Elasticity may be computed directly from

FIG. 9 – EXPANSION AND WEIGHT LOSS OF CONCRETES

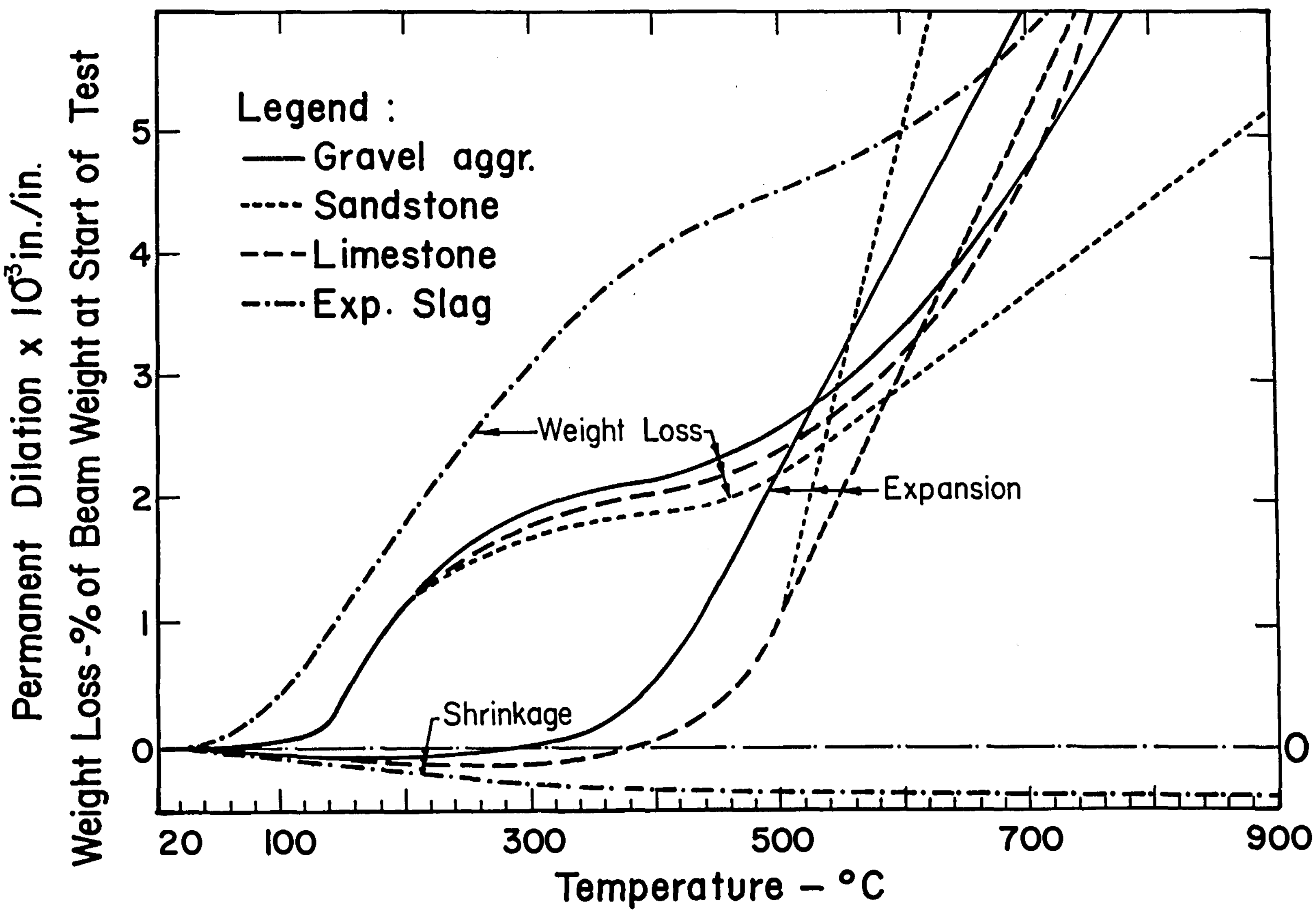


FIG. 10 LOSS OF FLEXURAL STRENGTH

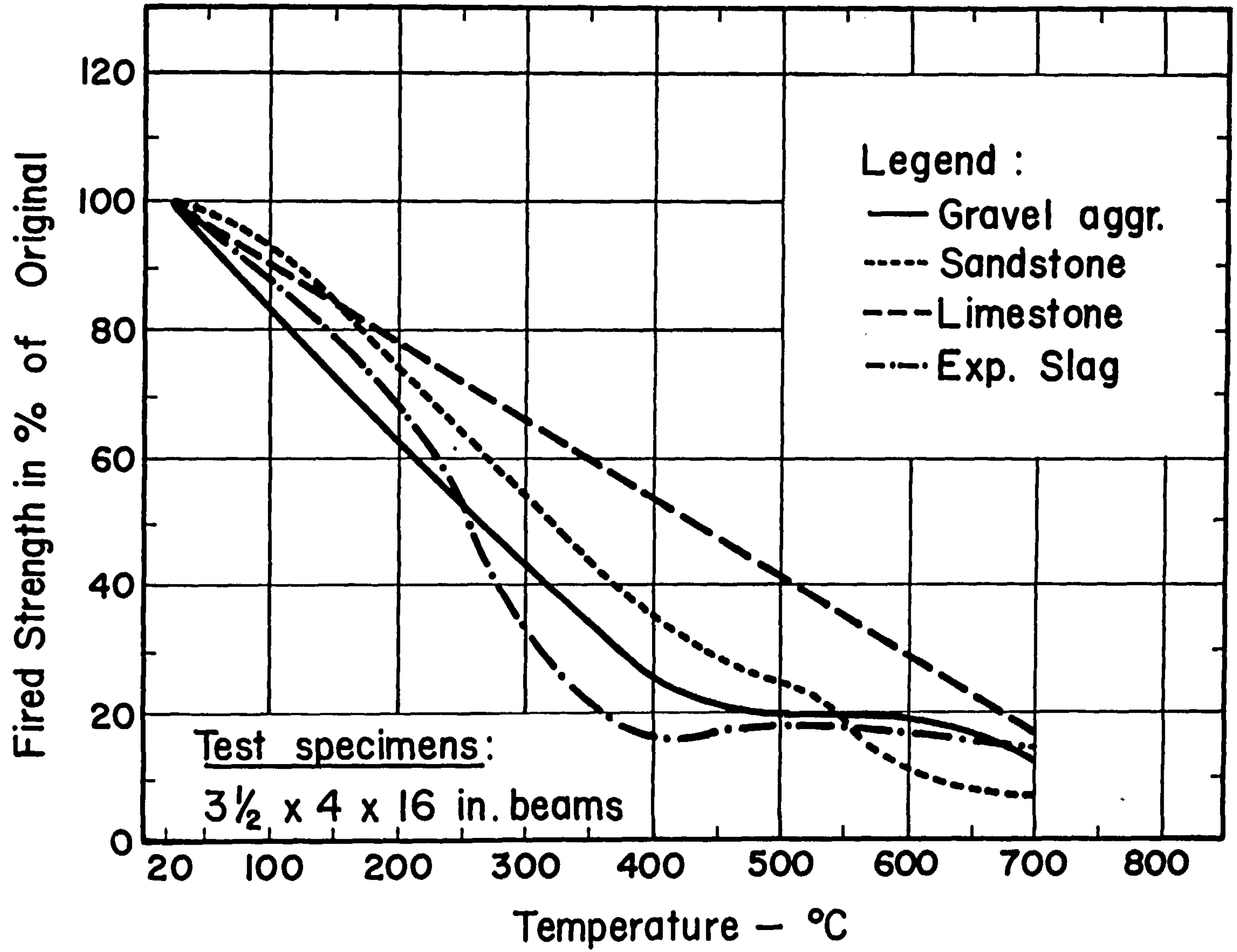
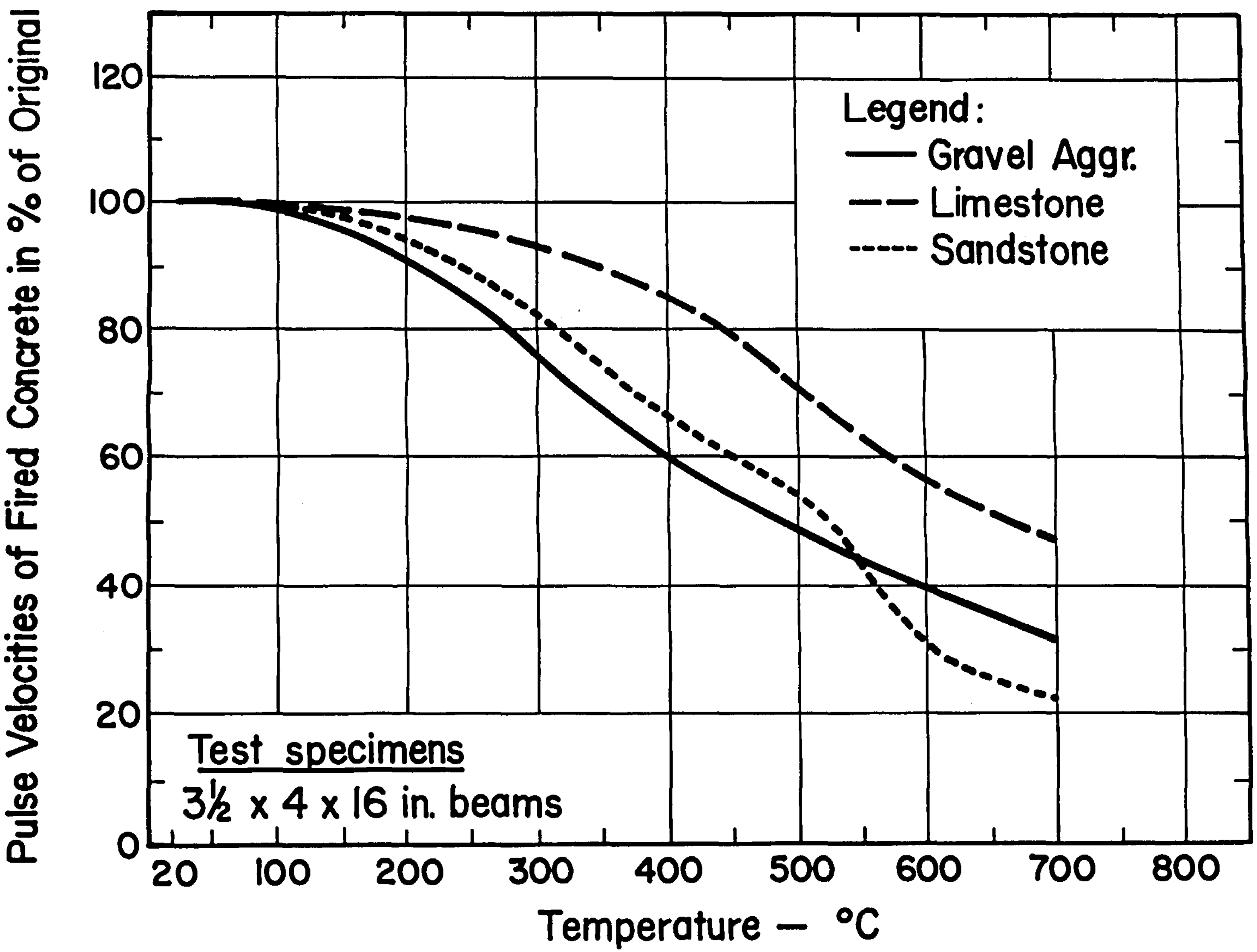


FIG. 11 LOSS OF ULTRASONIC PULSE VELOCITY



pulse velocity (V) if the density (d) of concrete is known:[7]

$$E_{dyn} = 1.83\, d\, V^2\, 10^{-4} \text{ psi.}$$

This equation shows that any change in structural properties of concrete will affect the dynamic modulus in proportion to the square of the pulse velocity.

Damage to concrete by exposure to elevated temperatures is more obvious if expressed in terms of moduli of elasticity than if shown in terms of pulse velocity.[8]

Table 12 compares the measured original and residual pulse velocities (V), and computed values of dynamic modulus of elasticity (E), of gravel, sandstone and limestone concretes exposed to temperatures of 400 and 700°C. The residual values are also expressed as percentages of the original values.

A study of curves in Figures 10 and 11, as well as values of dynamic modulus of elasticity (E_{fin}) in Table 12, shows that limestone concrete retains its structural strength at elevated temperatures, up to 700°C, better than any of the other three concretes investigated.

For temperatures below 500°C, the second best was sandstone concrete. Exposed to temperatures over 500°C, the same concrete showed a rapid loss of strength, which was confirmed also by a sudden drop in pulse velocity. This phenomenon seems to be connected with the inversion of quartz from α to β form at 573°C.[9] This inversion causes a volume expansion of about 2.4%, resulting in shattering of crystals.[10] The rapid expansion of sandstone concrete at this temperature is shown in Figure 9.

An even more detrimental expansion of sandstone concrete may be expected at 870°C, when quartz inverts to tridymite with an accompanying volume increase of 14%.[10]

TABLE 12

Changes of Elastic Properties in Concrete After Firing

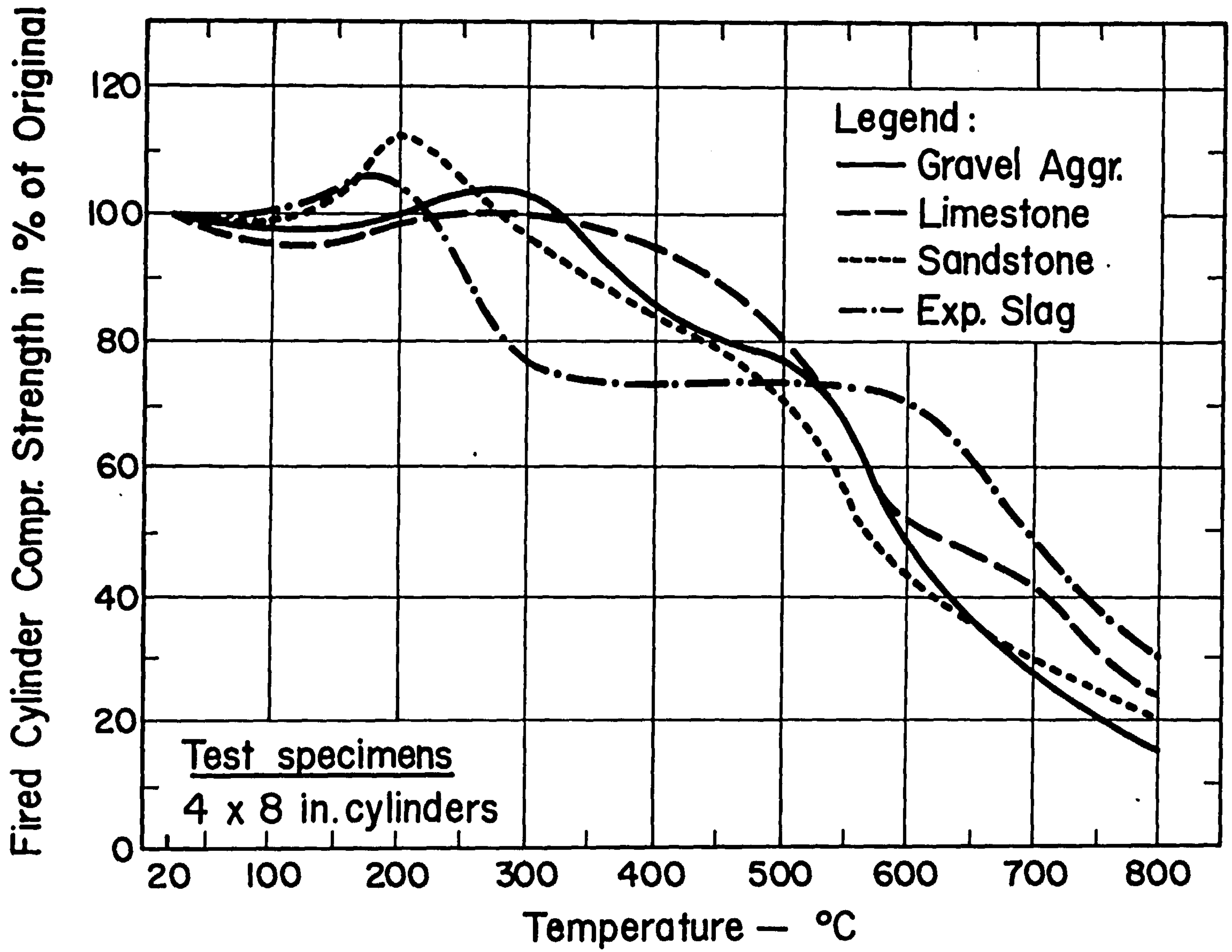
Types of Concrete	Temp., °C	Pulse Velocity, f sec			Dynam. Mod. Elast., psi		
		Vo $\times 10^3$	Vfin $\times 10^3$	Vfin %	Eo $\times 10^6$	Efin $\times 10^6$	Efin %
Gravel Concrete	400	14.128	9.802	69.4	5.25	2.48	47.2
	700	14.715	4.402	30.0	5.70	0.49	8.6
Sandstone Concrete	400	13.512	8.774	64.9	4.58	1.89	41.3
	700	13.006	3.055	23.5	4.23	0.23	5.3
Limestone Concrete	400	14.962	12.678	84.7	5.85	4.12	70.4
	700	14.952	6.900	46.1	5.84	1.19	20.4

Abbreviation: Vo and Eo - original values before firing.
Vfin and Efin - residual values after firing.

Curves in Figure 12, plotted from data compiled in Table 8, show changes in compressive strength in cylinders.

In general, the results indicated that after heating to 200 or 300°C the residual compressive strength of concrete increased up to 10% over the original strength. This may be explained partly by heat-stimulated cement hydration with water, still available in the room-dried test specimen, and partly by the densifying process of cement gel due to the loss of physically adsorbed water.[11]

FIG. 12 LOSS OF CYLINDER COMPRESSIVE STRENGTH



The strength increase was more pronounced in concrete made with sandstone aggregate. Apparently, some free lime was still available in the cement paste to combine at higher temperatures with finely-divided silica in sandstone aggregate, thereby adding strength to the cement paste.[12, 13]

Strength dropped rapidly after exposures above 500°C, due to the dehydration of cement paste.[14] Deterioration effects were observed first in concretes of higher thermal diffusivity (heat penetrating properties). Expanded slag concrete, the heat diffusivity of which is only half that of sandstone concrete, began to disintegrate at a furnace temperature about 100 degrees higher.

CONCLUSIONS

Within the scope of this investigation, it is concluded that portland cement concrete prepared with commercial aggregates deteriorates on exposure to dry heat at elevated temperatures. Extended deterioration of concrete is dependent to a large degree on the type of the aggregate.

Results showed evidence that flexural strength is more seriously affected by such exposure than is compressive strength.

The effect of different aggregates on the relative fire resistance of concrete may be summarized as follows:

(1) Concrete made with igneous gravel deteriorated more rapidly than limestone concrete. After 400°C exposure, the residual flexural strength of gravel concrete was only 26 per cent, and the

compressive strength only 85 per cent, of the original strength.

(2) Sandstone concrete showed a significant compressive strength gain in the lower temperature ranges. Above 500°C it deteriorated, losing strength rapidly.

(3) Limestone concrete performed best of the four concretes investigated, after being exposed to temperatures up to 700°C.

(4) Expanded slag concrete was strong in compression, retaining 71 per cent of its original strength after exposure at 600°C, but it retained only 16 per cent of its flexural strength after exposure to 400°C.

ACKNOWLEDGMENTS

Several staff members of the Mineral Processing Division assisted in providing specific test data and facilities in this work. Particularly, the author is indebted to Messrs. J. G. Brady, J. A. Soles, V. D. Svikis and L. K. Zemgals, for special contributions to the project.

Grateful acknowledgment is made to Mr. Nolan D. Mitchell, structural engineer and fire protective consultant, Arlington, Va., for advice in planning the fire-testing procedures, and to Mr. T. C. Powers, of the Portland Cement Association, Skokie, Ill., for help in interpretation of test results on fired concrete test specimens.

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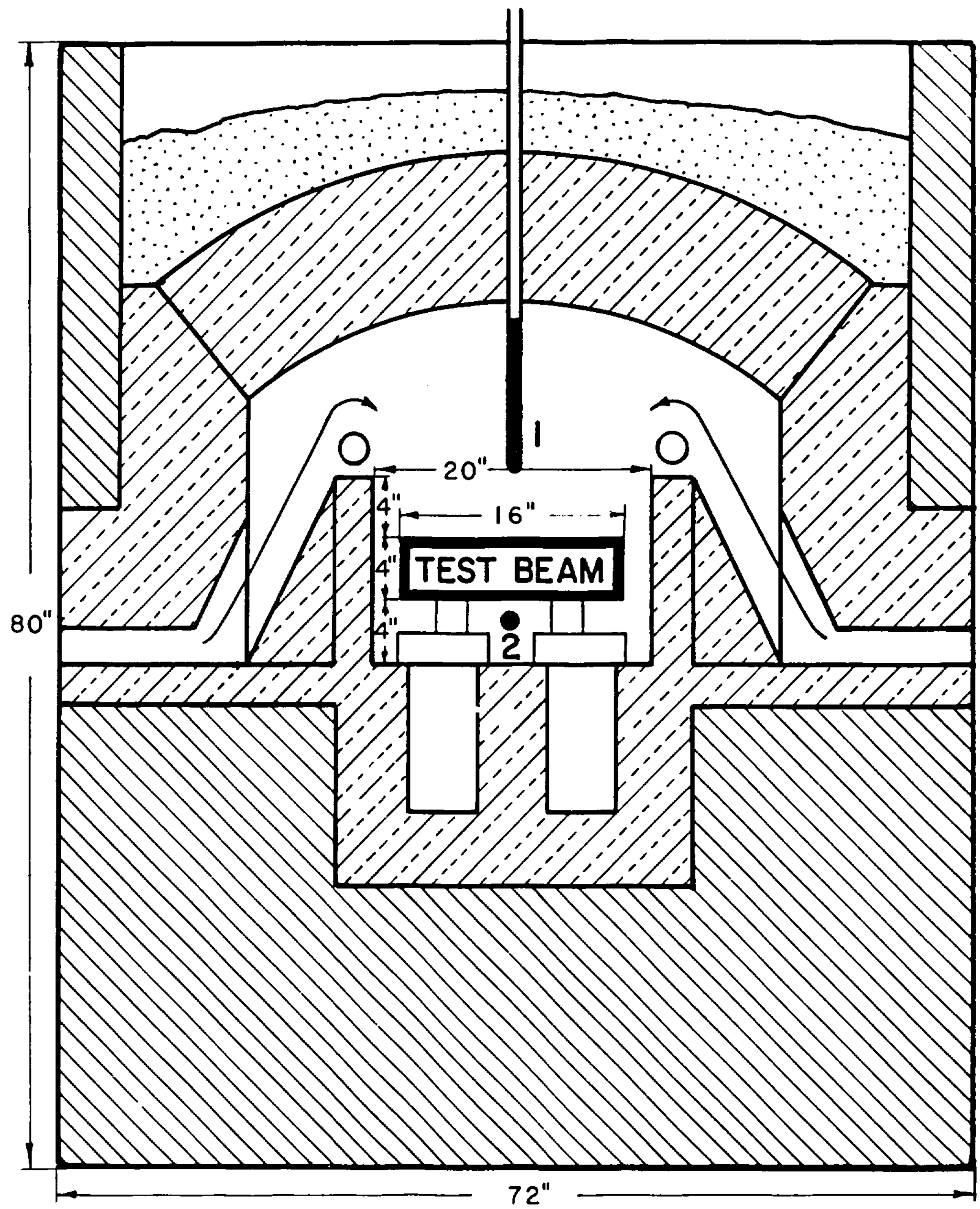
APPENDIX I

DOWN-DRAFT GAS-FIRED FURNACE

(used for concrete firing tests)



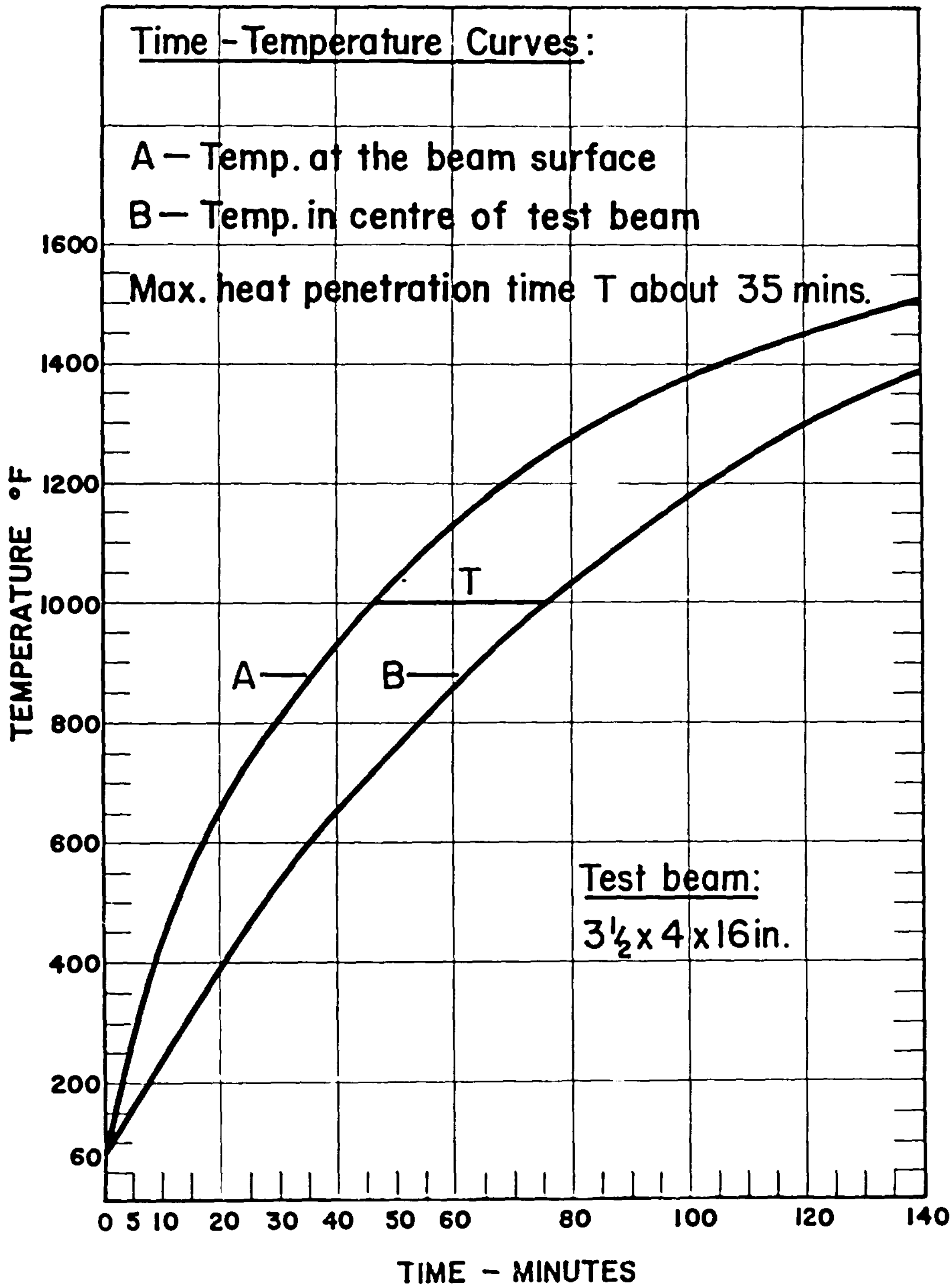
1 - Top thermocouple (vertical)

2-Bottom thermocouple (horizontal)

Preliminary firing data

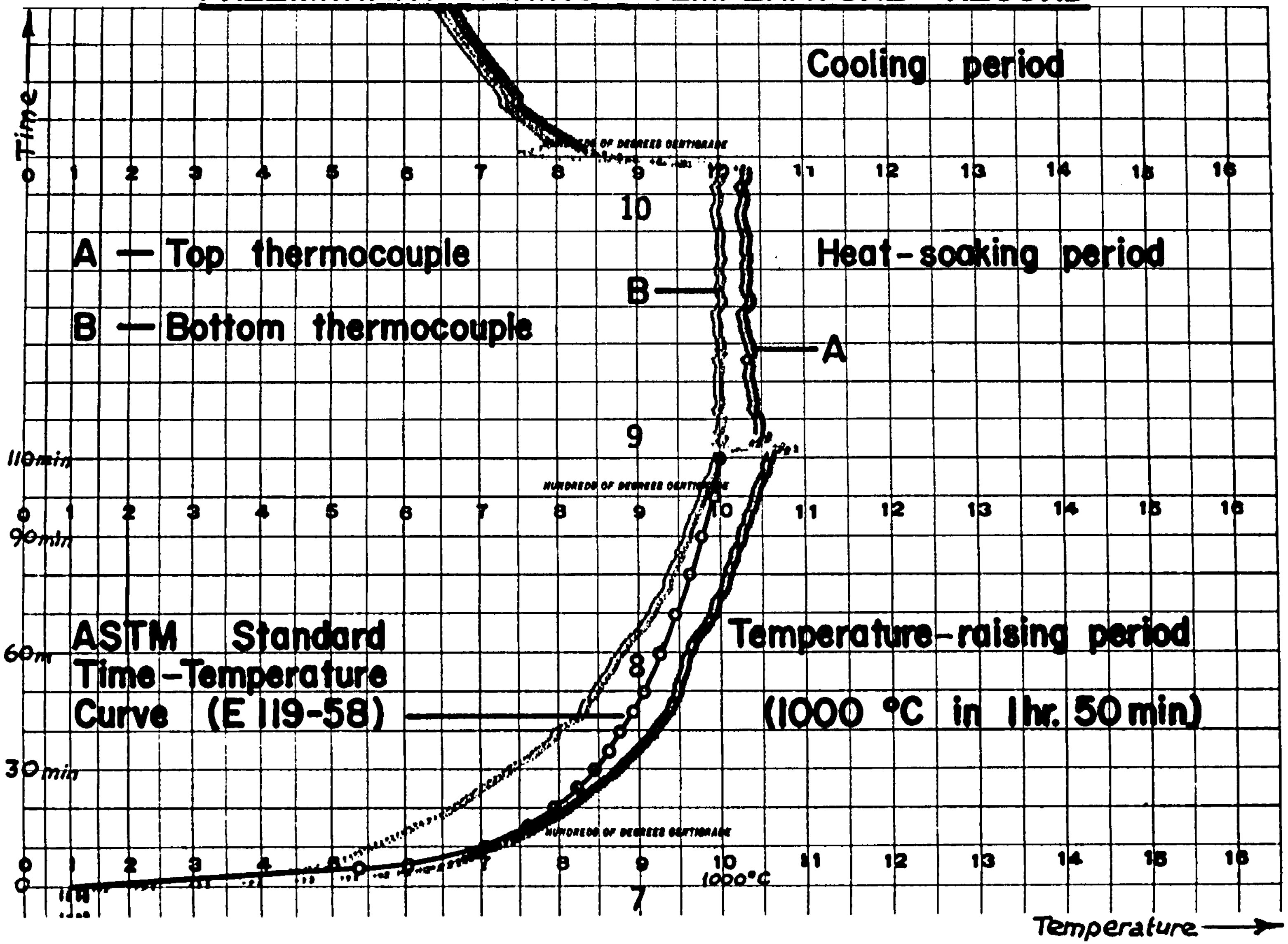
APPENDIX 2

HEAT PENETRATION



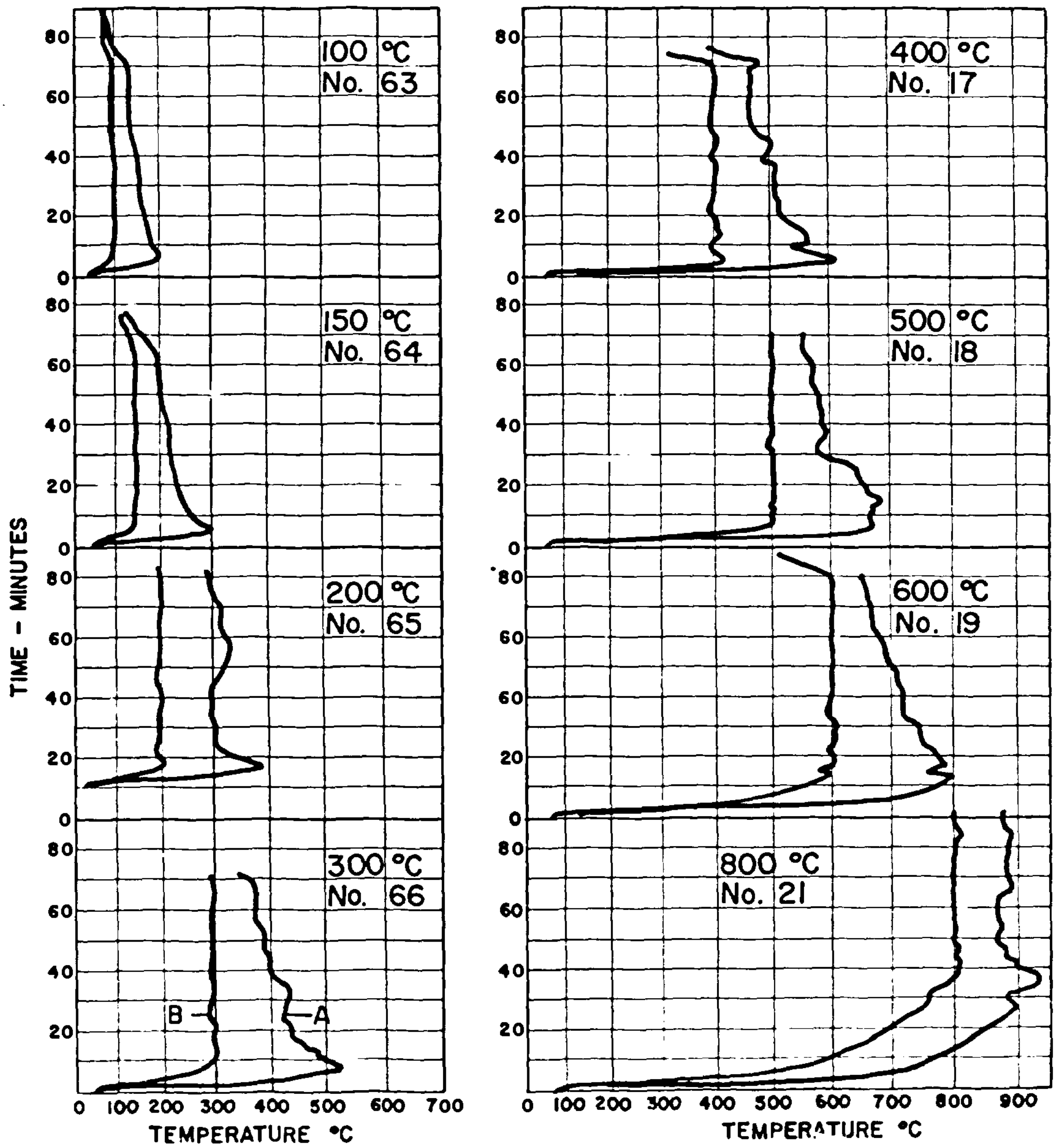
APPENDIX 3

PRELIMINARY FIRING – TEMPERATURE RECORD



APPENDIX 4

FURNACE TEMPERATURE RECORDS

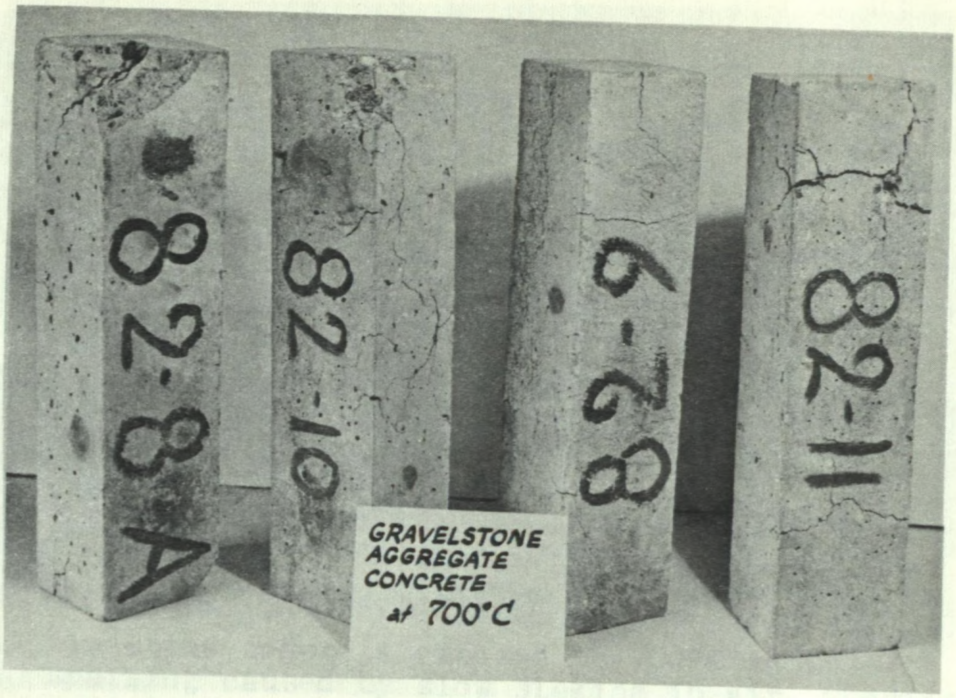


A – TOP THERMOCOUPLE

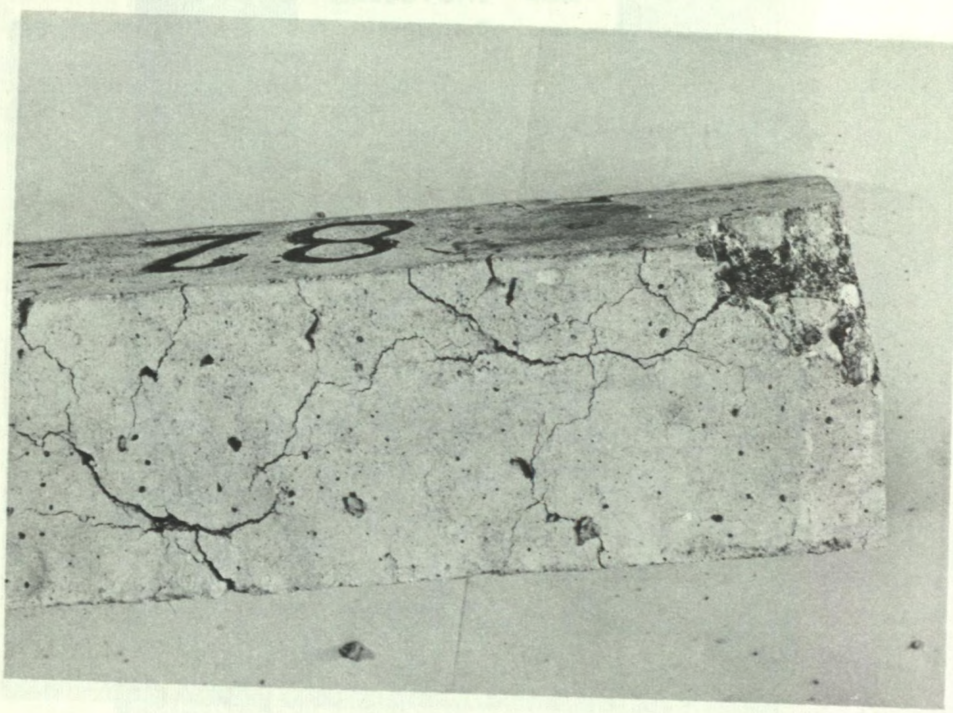
B – BOTTOM THERMOCOUPLE

APPENDIX 5

Photographs of damaged concrete specimens, slowly cooled or quenched, after heating:

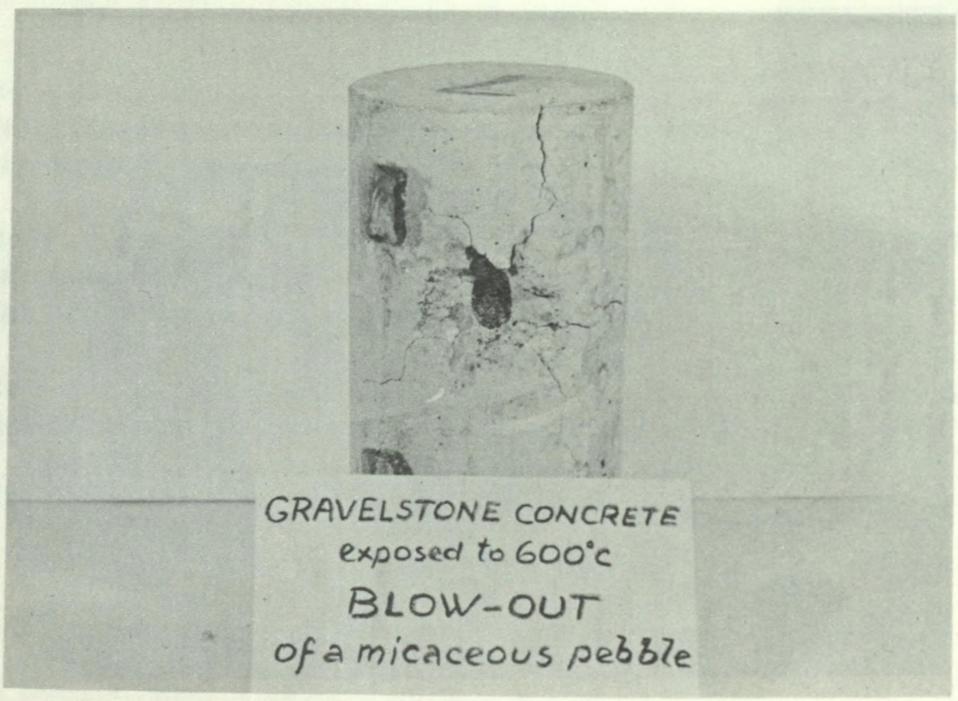


A. Extensive cracking of concrete beams caused by expanding aggregate particles.

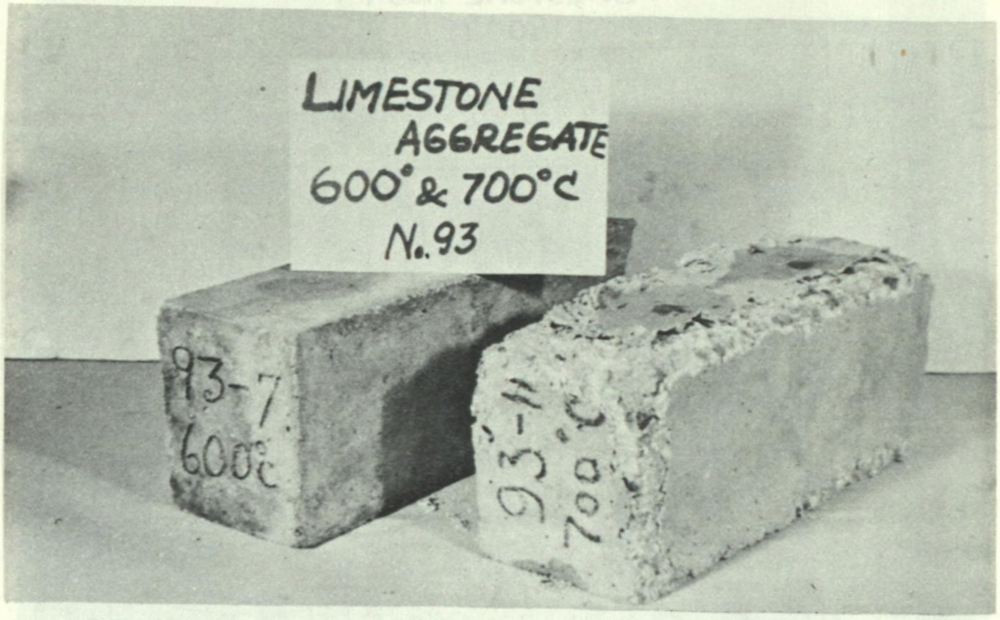


B. Detailed view on cracking pattern of a damaged beam.

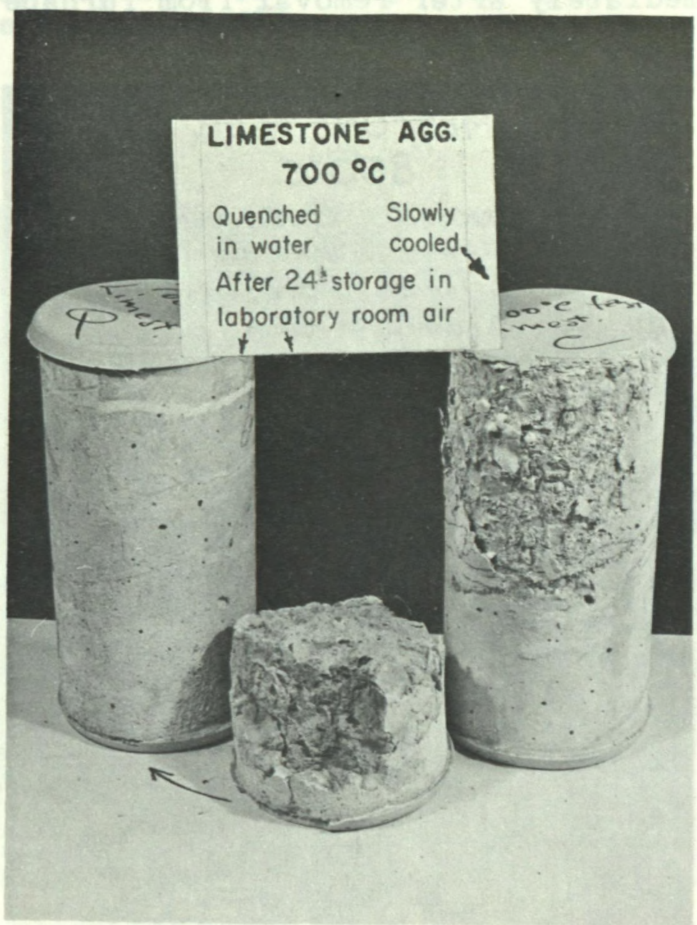
A. Cracked and disintegrated cylinders, retaining only 15% of original strength.



B. Radial cracks and "pop-out" caused by a micaceous pebble.

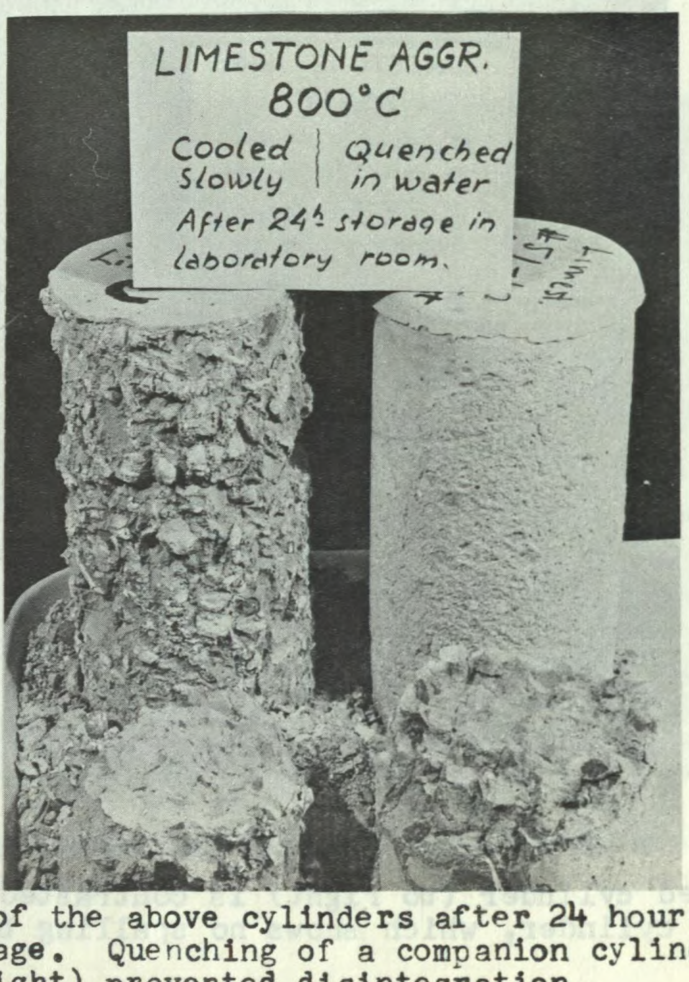


A. Limestone concrete exposed to 700°C shows spalling caused by slow slaking in air, whereas same concrete exposed to 600°C shows no effect.

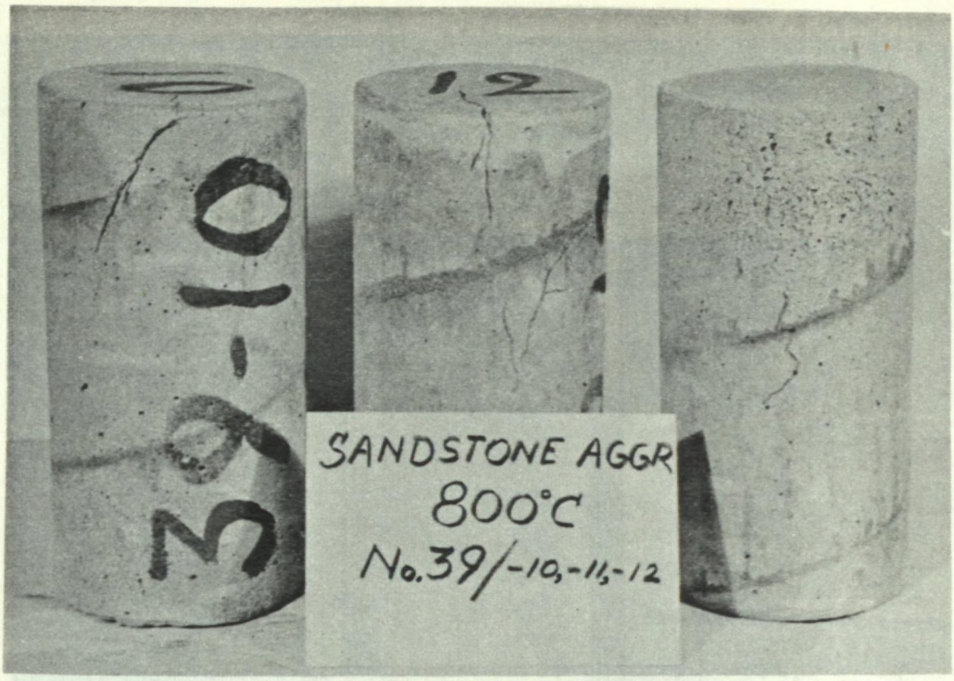


B. Air-cooled cylinder (to right) is contrasted with quenched cylinder, which shows no spalling by slaking.

A. Unspalled limestone concrete photographed immediately after removal from furnace.

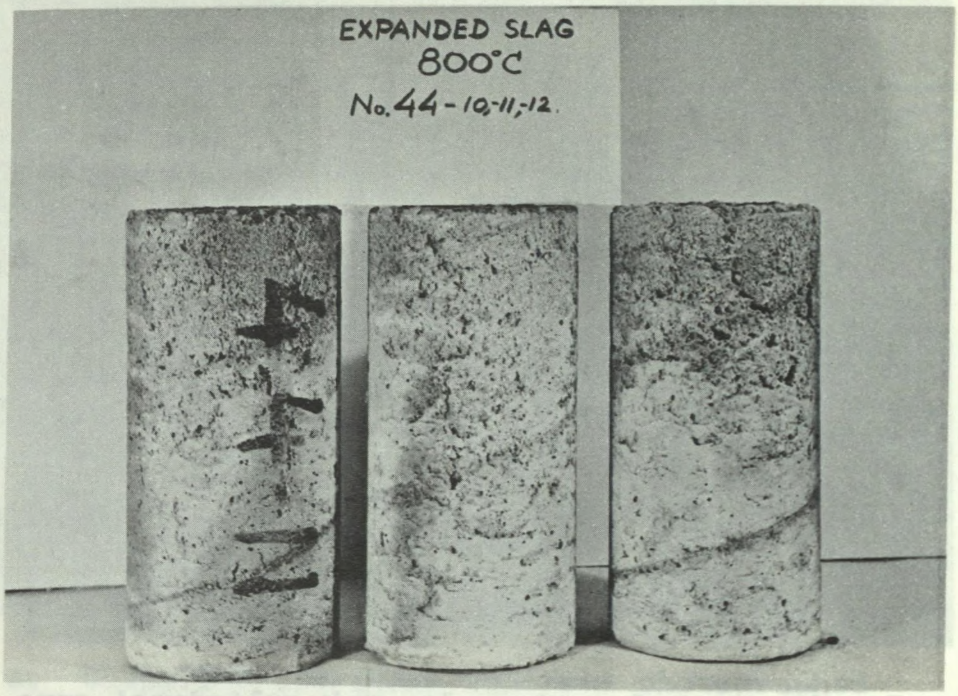


B. Two of the above cylinders after 24 hours of air storage. Quenching of a companion cylinder (on right) prevented disintegration.

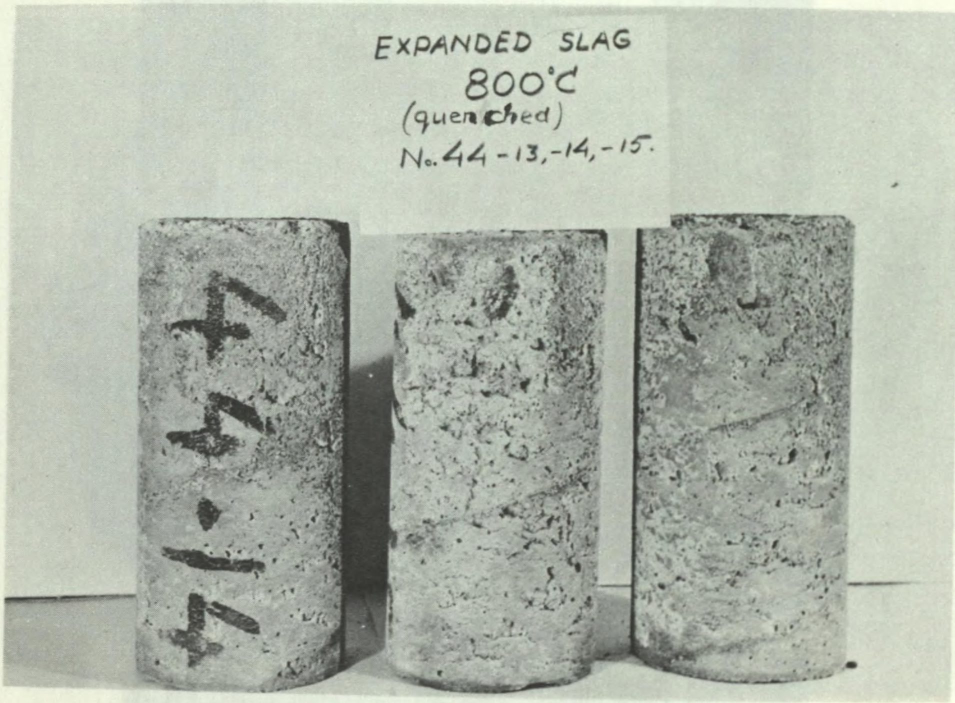


A. Finely cracked, extremely weak cylinders; some broke during handling.

B. Rim of hardened concrete produced by re-hydration of cement during quenching.



A. Unruptured expanded slag cylinders. Dehydrated cement paste has lost its bond with aggregates.



B. Quenching of cylinders has re-hydrated cement paste, producing a non-flaking skin of sound mortar.