Fire tests on reinforced concrete columns: specimen no. 10

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ABSTRACT

Results of a fire test on a reinforced concrete column are given. The test is one of a series of twelve tests carried out in the first phase of a joint study on the fire performance of concrete columns by the National Research Council Canada and the Portland Cement Association. The column was made with carbonate aggregate. Its section size was 305 × 305 mm (12 × 12 in.). It was tested to determine the influence of aggregate on the fire resistance of the column.

FIRE TESTS ON REINFORCED CONCRETE COLUMNS
SPECIMEN NO. 10

by

T.T. Lie and T.D. Lin*

Tests were carried out on a series of reinforced concrete columns as part of a study to develop methods for the determination of the fire resistance of such columns. The study was a cooperative effort between the National Research Council Canada and the Portland Cement Association. In the first phase of the study 12 columns were tested. The columns were designed and manufactured by PCA in Skokie, Illinois, and tested in the NRCC laboratories in Ottawa. The specimens, method of testing and test results are described in successive reports.

This report deals with specimen No. 10, which was tested to determine the influence of the aggregate on the fire resistance of the column.

TEST SPECIMEN

The specimen consisted of a square tied reinforced concrete column. Details of the specimen and its fabrication are given below.

Dimensions

Section size: 305 × 305 mm (12 × 12 in.)
Height: 3810 mm (12 ft 6 in.)

Materials

Cement: Type I, a general purpose cement for construction of reinforced concrete structures.

Aggregate: Carbonate sand and gravel from Elgin, Illinois. Maximum size of aggregate was 19 mm (3/4 in.). The gradation curve is shown in Fig. 1. Petrographic information given in Table 1 was obtained following the procedures of ASTM C295-79[1].

Physical properties of aggregate: Specific gravity of sand (2.67); specific gravity of gravel (2.67); moisture content of sand (3.0%); moisture content of gravel (1.0%); saturated surface dry unit weight of gravel (1712 kg/m^3) (107.0 lb/ft^3); fineness modulus of fine aggregate (3.00); fineness modulus of coarse aggregate (1.53).

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Steel reinforcement: Deformed 25M (No. 8) longitudinal reinforcing bars and 10M (No. 3) ties, meeting the requirements of ASTM Designation A615-60[2]. The yield stress of the 25M bars was 443.7 MPa (64.3 ksi) and that of the 10M bars 426.5 MPa (61.8 ksi). The ultimate strength of the 25M bar was 730 MPa (105.8 ksi) and of the 10M bar, 671 MPa (97 ksi).

Concrete mix: The concrete mix was designed to produce a 34.5 MPa (5000 psi) strength non-air-entrained concrete. A water/cement ratio of 0.6 was used. The slump was 76 mm (3.0 in.). Batch quantities are as follows: cement, 346 kg/m^3 (583 lb/yd^3); coarse aggregate, 1066 kg/m^3 (1796 lb/yd^3); sand, 816 kg/m^3 (1375 lb/yd^3); water, 193 kg/m^3 (325 lb/yd^3). The measured properties of the concrete were: air content, 2.17%; density, 2396 kg/m^3 (149.5 lb/ft^3); compressive strength at 28 days (cast date, 19 August 1977), 33.6 MPa (4875 psi).

Fabrication

Casting

The column was cast in a specially designed form. At the start of casting, the front of the form was left open for depositing fresh concrete. The concrete was mixed in a 0.17 m^3 (6 ft^3) tilting drum mixer. Shovels and scoops were used to deposit concrete in the form. A small internal vibrator was applied to consolidate the concrete. As casting progressed upwards, the window pieces were successively closed and tightly bolted to the form to avoid possible moisture leaks. Lifting hooks were embedded on opposite sides of the test specimen at 800 mm (2 ft 7 1/2 in.) from the top of the column. A cylindrical humidity well[3] with a diameter of 4 mm (5/32 in.) was positioned at mid-height of the column for measuring the relative humidity at mid-depth.

Reinforcing cage

The reinforcing cage was assembled by welding each end of four longitudinal main reinforcing bars to a steel end plate. The bars were cut to 3800 mm (12 ft 5 1/2 in.) and machined at both ends, for a length of 19 mm (3/4 in.) to a diameter of 19 mm. Fig. 2 shows details of the finished bars. The dimensions of the end plates were 533 × 533 × 25 mm (21 × 21 × 1 in.). In each corner of the plate, 20.6 mm (13/16 in.) holes were drilled to accommodate the longitudinal bars. The centers of the holes were spaced 92.1 mm (3 5/8 in.) from the centrelines of the plates. In this way a column was obtained with a section of 305 × 305 mm (12 × 12 in.) and a cover of 47.6 mm (1 7/8 in.) to the main reinforcing bars and 38.1 mm (1 1/2 in.) to the stirrups. The main bars and stirrups were tied together to complete the steel cage which, including the steel plates, was 3810 mm (12 ft 6 in.) long.

Welding

The provisions of AWS Designation D12.1-75[4] were followed when welding plates and bars. These members were preheated with a propane torch to 288°C (550°F), to prevent brittle failure during welding. The side fillet weld was done around bars on the inner face of the bottom plate. McKay E10018-D2 and DYTRON-579 welding rods were used. Both types of welding rods have tensile strength of 835 MPa (121 000 psi). Mild-steel welding rods were used to fill up the 6 mm (1/4 in.) deep holes on the outer faces of the plate. The rough surfaces of the welded joints on the outer face of the plate were ground to a smooth finish.

The welding of the top steel plate was performed after the casting of the columns. Before positioning the top plate, a 6 mm (1/4 in.) layer of mortar was spread over the top of the column to ensure good contact between steel and concrete. The mortar was made of one part cement and three parts siliceous sand. Using the same procedure as for the bottom plate, the top plate was welded on the outer side to the bars and smoothed.

Curing

The concrete was cured under damp burlap for 7 days at 21 to 24°C (70 to 75°F). The form was then stripped, and the column conditioned in an atmosphere controlled at 21 to 24°C and 30 to 40% relative humidity.

The column was removed from the kiln periodically to cool at 23°C (73°F) so that the relative humidity could be measured. Two hundred fifty-six days after casting, the relative humidity in the center of the column reached 85%, and the column was wrapped in plastic to prevent change of its moisture content.

Thermocouples

Butt-welded chromel-alumel thermocouples with a thickness of 0.912 mm (0.0359 in.) were used to make thermocouple frames for measuring concrete temperatures at different locations in various cross sections of the columns. Each frame consisted of a number of thermocouples tied to steel rods that were firmly secured to the main reinforcing bars. Temperatures were measured at three levels: at one-quarter height, at mid-height and at three-quarter height of the column. At mid-height the temperatures were measured along the whole length of a centerline and diagonal of the section; at the other two levels the temperatures were measured only along half of the centerline and half of the diagonal of the section. The location of the thermocouples in the concrete and their numbering are shown in Figs. 3 and 4.

In addition, a number of thermocouples were mounted on the reinforcing steel bars and ties. The locations of the thermocouples on the steel are shown in Fig. 5 and in more detail in Fig. 6.

All thermocouples were installed in such a way that the wire followed an isotherm for at least 12.7 mm (1/2 in.) from the junction.

Test Apparatus

The test was carried out by exposing the column to heat in a furnace specially built for testing loaded columns and walls. The test furnace was designed to produce the conditions to which a member might be exposed during a fire, i.e. temperatures, structural loads, and heat transfer. It consists of a steel framework supported by four steel columns, with the furnace chamber inside the framework (Fig. 7). The characteristics and instrumentation of the furnace are described in detail in reference 5. Only a brief description of the furnace and the main components will be given here.

Loading Device

Three hydraulic jacks produce forces along the three principal axes. The jack acting along the axis of the test column is located at the bottom of the furnace chamber. The plate on top of this jack can be used as a platform to which the column can be attached.

Furnace Chamber

The furnace chamber has a floor 2642 mm (8 ft 8 in.) on each side and is 3048 mm (10 ft) high. It is made of insulating materials that will produce a high heat transfer to the specimen. There are 32 propane gas burners in the furnace chamber, arranged in eight columns containing four burners each. The total capacity of the burners is 4700 kW (16 million Btu/h). Each burner can be adjusted individually, which allows a high temperature uniformity in the furnace chamber. The pressure in the furnace chamber is also adjustable. It was set somewhat lower than atmospheric pressure.

Instrumentation

The furnace temperatures are measured with the aid of eight chromel-alumel thermocouples. The junction of each thermocouple was located 305 mm (1 ft) from the test specimen at various heights. Two thermocouples are placed opposite each other every 610 mm (2 ft) along the height of the furnace chamber. The location of their junctions and their numbering are shown in Fig. 8. Thermocouples No. 4 and 6 were located at a height of 610 mm (2 ft) from the floor, thermocouples No. 2 and 8 at 1220 mm (4 ft), thermocouples No. 3 and 5 at 1830 mm (6 ft) and thermocouples No. 1 and 7 at 2440 mm (8 ft). The temperatures measured by the thermocouples are averaged automatically and the average temperature used as the criterion for controlling the furnace temperature.

The loads are controlled and measured with the aid of pressure transducers. The accuracy of controlling and measuring loads is about 20 kN (5 kips) at lower load levels and better at higher loads.

The axial deformation of the test specimen is determined by measuring the displacement of the jack that supports the column. The displacement is measured with the aid of transducers with an accuracy of 0.002 mm (7.87×10^{-5} in.).

Test Conditions and Procedure

The column was installed in the furnace by bolting its end plates to a loading head at the top and a hydraulic jack at the bottom. Eight 19 mm (3/4 in.) bolts, spaced regularly around the column 63.5 mm (2 1/2 in.) from the sides, were used at each end.

On the day of the test, the moisture condition in the center of the column was measured with a Monfore gauge[3]. The relative humidity measured prior to the start of the test was 75%. The ambient temperature at the start of the test was 15°C (59°F).

The column was subjected to a load of 800 kN (180 kips), which was applied about one hour prior to the test. The compressive strength of the concrete on the test date, measured on one cylinder, was 40.9 MPa (5925 kips). The column was cast on the 19th of August 1977 and tested on the 14th of December 1981.

During the test the column was exposed to heating that was controlled so that the average temperature in the furnace followed as closely as possible the ASTM-E119[6] or ULC-S101[7] standard temperature-time curve. This curve can be approximately described by the following equation:[8]

$$T_f = 20 + 750\left[1-\exp(-3.79553\sqrt{\tau})\right] + 170.41\sqrt{\tau} \qquad (1)$$

where

T_f = temperature in °C, and
τ = time in h

or by

$$T_f = 68 + 1350\left[1-\exp(-3.79553\sqrt{\tau})\right] + 306.74\sqrt{\tau} \qquad (2)$$

where

T_f = temperature in °F.

During the test, temperatures in the furnace and in the column were measured at the locations described earlier. The axial strain of the column was also measured. The column was regarded to have failed,

and the test was terminated, when the hydraulic jack, which has a maximum speed of 76 mm/min (3 in./min), could no longer maintain the applied load.

TEST RESULTS

Measured Temperatures and Strains

In Tables 2A-C the steel temperatures are given for various times. The temperatures measured in the concrete sections are listed in Tables 3A-D.

In Table 4 the average furnace temperatures, and in Table 5 the measured axial deformation of the column, are given for various times during the test.

Observations

The observations made during the test after various exposure times are given below.

Test time Hr:Min	
0.0	Fire started.
2:05	Small hairline cracks 51 to 76 mm (2 to 3 in.) long were viewed on the east face of the column. Subsequently, small cracks appeared on other faces.
2:30	The maximum expansion of 14 mm (0.55 in.) was reached and decreased thereafter.
4:30	All cracks on column developed within the first 4 1/2 hrs. After this point, cracks progressively extended and slowly widened.
5:00	Cracks on the east face were about 300 mm (12 in.) long and 6.4 mm (1/4 in.) wide. Cracks on other faces also worsened.
6:30	The column expansion returned to its initial zero stage and the column started to contract under load.
7:00	Steel temperature exceeded 760°C (1400°F).
8:00	Steel temperature reached 816°C (1500°F).

8:10 The contraction was 20 mm (0.79 in.) and accelerated.

8:30 The column contracted to 24 mm (0.94 in.). At this moment, the column finally failed in compression with a mild crushing sound. Fire was immediately turned off.

In Fig. 9 the column is shown after the test.

DISCUSSION OF RESULTS

Figure 10 shows average temperatures obtained from measurements on two reinforcing bars during the test. These measurements were made with thermocouples No. 3 and 9 located opposite to each other with respect to the center of one bar (Fig. 6).

The temperatures measured on the steel by the individual thermocouples are shown in Fig. 11.

No calculations were made of the fire resistance of this column, because the material properties of the carbonate aggregate concrete of which the column was made, were not known sufficiently. A comparison with the fire resistance of a similar column[9], made with siliceous aggregate and tested under the same load, shows that the resistance of the carbonate aggregate concrete column was more than twice that of the siliceous aggregate concrete column.

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TABLE 1 PETROGRAPHY OF SAND AND GRAVEL USED AS AGGREGATE

Component	Composition of Sieve Fraction, Percent on Sieve of Size Indicated											Percent passing through No. 200
	19 mm	12.5 mm	9.5 mm	6 mm	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	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	19 to 6 mm (%)		No. 4 to No. 200 (%)	
	Carbonates	Silicates	Carbonates	Silicates
Rounded	—	—	—	30
Subangular to subrounded	80	100	75	60
Angular	—	—	—	10
Angular to subangular	20	—	25	—

TABLE 2A MEASURED STEEL TEMPERATURES

Time (min)	Temperature (°C) Measured at Thermocouple No: 1	2	3	4	5	6	7	8	9	10
0	20	18	17	*	12	6	8	15	17	17
5	29	25	25	*	19	12	28	19	19	20
10	45	42	44	*	34	26	59	67	32	29
15	86	85	90	*	89	67	103	107	65	60
20	107	104	107	*	108	106	121	131	93	96
25	113	109	114	*	109	111	149	163	107	108
30	127	122	140	*	122	118	181	193	109	*
35	147	145	164	*	138	133	213	219	124	115
40	171	170	190	*	161	154	242	244	145	134
45	196	196	218	*	185	178	269	268	169	154
50	222	222	245	*	209	204	293	292	192	176
55	246	247	272	*	233	229	315	315	215	197
60	270	270	296	*	256	253	335	337	237	219
65	292	292	318	*	278	276	353	358	259	239
70	313	312	338	*	299	297	369	377	280	259
75	333	331	357	*	319	317	384	395	300	278
80	351	348	374	*	338	335	398	413	318	296
85	368	364	390	*	355	353	411	429	335	313
90	385	380	405	*	372	369	423	444	352	330
95	400	394	418	*	387	385	435	459	367	346
100	414	407	432	*	402	399	446	472	382	361
105	427	420	444	*	416	413	456	485	396	376
110	440	432	456	*	429	426	466	496	409	389
115	453	444	468	*	442	438	475	507	422	403

*Measurement not reliable

TABLE 2B MEASURED STEEL TEMPERATURES

Time (min)	Temperature (°C) Measured at Thermocouple No: 1	2	3	4	5	6	7	8	9	10
120	464	455	479	*	454	450	485	516	435	416
125	476	466	489	*	466	461	493	526	446	428
130	487	477	500	*	477	471	502	534	458	440
135	497	487	509	*	488	482	510	542	468	452
140	507	496	518	*	498	491	518	549	479	463
145	516	505	527	*	508	501	526	556	489	474
150	525	514	535	*	517	509	533	563	498	484
155	533	522	543	*	526	517	540	569	507	493
160	541	530	550	*	534	525	547	575	515	502
165	549	537	557	*	542	533	554	581	523	511
170	556	544	564	*	549	541	560	587	531	520
175	563	551	571	*	557	548	566	593	538	528
180	570	557	577	*	563	554	572	599	545	535
185	576	563	584	*	570	561	578	605	552	543
190	582	569	590	*	576	567	583	610	559	550
195	588	575	596	*	582	573	589	615	565	556
200	593	580	601	*	588	579	594	621	571	563
205	599	586	607	*	593	584	599	626	577	569
210	604	591	612	*	599	589	604	631	583	575
215	609	596	618	*	604	594	609	636	588	580
220	614	600	624	*	609	599	614	640	594	586
225	619	605	629	*	614	604	619	645	599	591
230	625	610	635	*	619	609	623	649	604	596
235	630	615	640	*	624	613	628	654	609	601

*Measurement not reliable

TABLE 2C MEASURED STEEL TEMPERATURES

Time (min)	Temperature (°C) Measured at Thermocouple No: 1	2	3	4	5	6	7	8	9	10
240	635	619	651	*	629	617	632	658	614	607
245	640	624	652	*	634	622	637	662	618	611
250	645	628	659	*	639	626	641	666	623	617
255	651	633	664	*	644	630	645	669	628	622
260	657	638	668	*	649	634	649	673	632	627
265	663	642	672	*	654	638	653	675	637	632
270	669	647	675	*	658	643	657	677	641	637
275	674	651	678	*	663	647	661	679	646	642
280	680	656	680	*	667	651	665	681	650	647
285	685	660	681	*	672	655	668	682	654	653
290	690	665	682	*	676	659	671	683	657	658
295	694	668	684	*	679	664	674	683	*	663
300	698	672	685	*	683	668	677	685	659	667
310	705	679	687	*	689	677	681	687	666	676
320	711	686	691	*	695	685	685	694	673	684
330	716	692	695	*	700	693	688	699	680	692
340	721	697	699	*	704	700	690	703	685	697
350	726	702	707	*	708	707	693	707	690	703
360	732	708	726	*	712	713	696	*	694	710
370	*	712	743	*	713	721	*	*	696	716
380	*	717	*	*	713	726	*	*	*	722
390	*	*	*	*	713	729	*	*	*	728
400	*	*	*	*	714	732	*	*	*	733

*Measurement not reliable

TABLE 3A-1 CONCRETE TEMPERATURES MEASURED WITH THERMOCOUPLES IN FRAME A

Time (min)	Temperature (°C) Measured at Thermocouple No:													
	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0	19	19	19	19	19	19	19	19	19	18	18	18	18	18
5	161	100	49	36	23	19	19	20	23	34	69	118	179	257
10	274	179	99	71	33	21	20	21	31	74	137	215	315	417
15	364	251	137	107	50	23	20	24	55	117	199	308	423	529
20	437	314	178	132	74	28	22	33	86	137	261	387	506	605
25	502	370	222	167	97	44	26	51	99	177	320	453	571	664
30	559	423	263	202	109	64	34	68	105	227	375	511	624	712
35	600	467	301	233	112	70	43	76	110	272	426	557	663	745
40	631	502	333	260	125	76	53	80	123	312	470	596	693	769
45	657	531	361	286	141	81	61	85	141	347	508	625	717	791
50	679	555	386	309	158	86	70	93	160	377	540	650	737	811
55	698	576	409	330	176	94	81	104	178	404	566	670	755	832
60	713	593	429	350	193	103	95	109	198	427	585	687	773	849
65	727	608	448	369	210	106	104	115	217	447	601	702	790	864
70	740	622	465	386	225	113	109	122	236	465	614	715	806	877
75	753	635	481	402	240	121	113	128	254	480	626	728	821	889
80	765	647	496	417	253	128	118	136	271	493	639	741	834	901
85	776	658	509	431	266	136	123	144	287	505	651	753	846	912
90	788	668	521	444	278	144	128	154	302	516	662	765	856	925
95	800	679	533	456	289	153	131	164	317	526	673	777	866	936
100	810	688	544	468	300	161	134	175	331	536	684	788	875	944
105	821	697	554	479	312	169	137	185	345	546	695	798	884	952
110	827	705	563	489	323	178	141	196	358	555	704	807	891	955
115	834	711	571	499	334	188	147	207	371	564	713	815	898	960

*Measurement not reliable

TABLE 3A-2 CONCRETE TEMPERATURES MEASURED WITH THERMOCOUPLES IN FRAME A

Time (min)	Temperature (°C) Measured at Thermocouple No:													
	11	12	13	14	15	16	17	18	19	20	21	22	23	24
120	841	718	579	508	345	198	156	218	383	572	720	822	906	965
125	847	725	587	517	356	209	167	229	395	579	728	830	914	968
130	851	730	594	525	367	221	180	241	407	587	736	836	919	969
135	*	733	601	533	378	233	193	252	419	594	742	840	919	*
140	*	736	607	540	389	246	206	264	430	601	747	842	919	*
145	852	740	613	547	400	258	219	277	441	607	752	845	921	*
150	856	744	619	554	411	271	231	289	452	613	757	848	924	*
155	860	749	625	561	421	283	243	301	462	619	762	851	928	*
160	864	753	631	568	431	295	255	312	471	625	767	855	931	*
165	868	758	637	574	441	307	267	323	481	630	771	858	935	*
170	872	762	642	581	450	318	279	334	489	636	776	861	938	*
175	876	767	648	587	459	330	291	345	498	641	780	864	941	*
180	880	772	654	593	468	341	302	356	506	646	784	867	945	*
185	881	776	659	599	477	351	313	366	514	651	788	870	946	*
190	882	779	664	605	485	362	324	376	522	656	792	871	946	*
195	887	783	668	610	493	372	335	386	529	660	795	873	949	*
200	892	787	673	616	500	382	345	395	536	665	798	876	954	969
205	896	792	678	621	508	391	354	404	543	670	801	879	957	970
210	900	796	683	626	515	401	364	413	550	674	805	883	961	970
215	904	800	687	631	521	410	374	422	556	679	808	886	964	970
220	909	805	692	636	528	418	383	431	562	683	811	890	968	970
225	913	809	696	640	534	427	392	439	568	687	815	895	973	970
230	917	814	701	645	540	435	400	447	574	692	819	900	976	*
235	924	819	705	650	546	443	408	455	579	696	823	904	981	*

*Measurement not reliable

TABLE 3A-3 CONCRETE TEMPERATURES MEASURED WITH THERMOCOUPLES IN FRAME A

Time (min)	Temperature (°C) Measured at Thermocouple No: 11	12	13	14	15	16	17	18	19	20	21	22	23	24
240	929	824	710	654	551	451	416	462	584	701	827	910	987	*
245	933	828	714	659	557	459	424	470	589	705	831	915	991	*
250	939	833	719	663	562	467	432	477	594	709	835	920	994	*
255	944	838	723	668	567	474	440	484	599	714	839	925	998	*
260	949	842	728	672	571	481	448	491	604	718	843	930	1002	*
265	953	846	732	676	576	487	456	497	608	721	847	934	1003	*
270	956	850	736	680	581	494	463	503	613	725	851	938	*	*
275	960	854	740	684	585	500	470	510	617	728	854	941	*	*
280	963	858	744	688	589	506	477	516	622	731	856	944	*	*
285	967	862	748	692	593	512	484	522	626	734	859	946	*	*
290	970	866	752	696	597	517	490	528	631	737	861	948	*	*
295	974	870	756	700	601	522	496	534	635	739	862	949	*	*
300	975	873	759	703	605	528	502	541	640	741	863	949	*	*
310	977	879	766	710	612	538	515	554	649	744	*	*	*	*
320	*	884	771	717	620	547	527	569	658	744	*	*	*	*
330	*	887	775	722	628	557	540	587	667	*	*	*	*	*
340	*	891	777	*	636	567	554	606	676	*	*	*	*	*
350	*	893	779	*	645	578	591	626	684	*	*	*	*	*
360	*	*	*	*	655	591	608	645	691	*	*	*	*	*
370	*	*	*	*	663	*	622	661	697	*	*	*	*	*
380	*	*	*	*	668	*	*	674	701	*	*	*	*	*
390	*	*	*	*	*	*	*	683	704	*	*	*	*	*
400	*	*	*	*	*	*	*	692	709	*	*	*	*	*

*Measurement not reliable

TABLE 3B-1 CONCRETE TEMPERATURES MEASURED WITH THERMOCOUPLES IN FRAME B

Time (min)	Temperature (°C) Measured at Thermocouple No: 25	26	27	28	29	30	31	32	33	34	35	36	37	38
0	16	16	16	16	16	17	17	16	17	16	16	16	17	16
5	162	99	46	28	19	17	17	17	20	112	66	30	185	270
10	280	183	102	62	26	18	17	18	28	217	136	77	334	438
15	370	256	137	99	42	21	18	22	51	314	206	100	442	543
20	443	320	180	123	68	26	20	30	85	394	272	117	525	617
25	506	375	222	147	86	36	24	44	106	463	335	149	588	674
30	559	426	262	181	94	51	32	57	*	521	390	179	638	719
35	598	468	299	211	102	67	42	68	107	565	437	209	674	751
40	628	502	332	240	109	78	52	79	122	599	479	239	701	778
45	653	530	360	265	121	87	62	89	141	626	513	270	724	802
50	673	553	386	289	135	93	72	98	161	649	541	300	744	823
55	691	574	409	311	149	101	85	107	181	670	564	327	763	842
60	707	590	429	331	163	105	96	115	201	688	584	352	781	858
65	720	605	448	349	178	108	104	124	221	702	600	374	795	872
70	734	619	465	365	192	115	108	131	239	715	615	393	809	886
75	746	632	480	381	206	122	110	138	257	728	627	412	823	900
80	758	644	495	396	220	129	111	144	275	739	639	429	836	913
85	770	655	508	410	234	137	116	152	291	750	650	445	847	925
90	782	666	521	423	247	145	121	161	307	760	660	460	856	938
95	793	677	533	436	260	154	126	172	323	770	670	475	866	950
100	804	686	544	449	273	165	132	183	338	779	680	489	875	960
105	813	695	554	460	286	176	139	196	353	789	689	502	884	968
110	820	703	564	472	299	187	148	209	367	798	699	515	892	971
115	826	710	573	483	312	198	157	221	381	806	708	526	*	977

*Measurement not reliable

TABLE 3B-2 CONCRETE TEMPERATURES MEASURED WITH THERMOCOUPLES IN FRAME B

Time (min)	Temperature (°C) Measured at Thermocouple No:													
	25	26	27	28	29	30	31	32	33	34	35	36	37	38
120	833	717	582	493	325	210	167	234	394	814	716	537	*	982
125	840	724	590	503	338	222	178	247	407	822	725	547	*	986
130	844	730	598	513	350	234	191	259	419	828	733	557	*	988
135	*	733	605	522	362	247	203	271	431	832	740	566	*	*
140	*	736	611	530	375	259	216	283	443	835	746	574	*	*
145	846	740	617	538	386	272	229	295	454	838	751	582	*	*
150	850	744	623	545	397	284	241	307	465	841	757	589	*	*
155	854	749	629	552	408	296	253	319	475	845	762	596	*	*
160	858	754	634	559	418	307	264	330	485	848	767	603	*	*
165	863	758	640	566	429	319	276	341	495	852	773	610	*	991
170	867	763	646	572	439	330	288	352	504	856	778	616	*	994
175	871	768	651	579	448	341	299	363	513	859	783	622	*	996
180	875	773	657	585	458	352	310	373	521	863	787	628	*	999
185	876	777	662	591	467	362	321	383	529	867	792	634	*	*
190	877	780	667	597	475	372	332	393	536	869	795	639	*	*
195	882	784	671	603	484	382	342	403	544	871	798	644	*	1000
200	887	788	676	609	492	391	352	412	551	875	802	650	*	1004
205	891	793	681	614	500	401	362	421	558	879	806	655	*	1007
210	895	797	686	620	507	410	372	430	564	883	809	660	*	1010
215	899	801	691	625	515	419	381	439	570	887	813	665	*	1013
220	903	805	696	630	522	427	389	447	576	891	816	669	*	1016
225	907	809	700	635	529	436	398	456	582	895	819	674	*	1019
230	910	812	705	640	535	444	407	464	587	899	822	678	*	1020
235	915	815	709	645	541	453	415	472	593	904	826	682	*	1024

*Measurement not reliable

TABLE 3B-3 CONCRETE TEMPERATURES MEASURED WITH THERMOCOUPLES IN FRAME B

Time (min)	Temperature (°C) Measured at Thermocouple No: 25	26	27	28	29	30	31	32	33	34	35	36	37	38
240	919	817	713	650	548	461	423	479	598	909	829	687	*	1025
245	920	818	718	654	554	468	431	486	603	913	832	690	*	1026
250	921	*	722	659	559	476	440	494	608	916	834	694	*	1028
255	*	*	725	663	565	484	448	501	613	919	836	698	*	1029
260	*	*	729	667	571	491	457	508	618	922	836	701	*	1029
265	*	*	733	671	577	499	465	515	623	922	*	704	*	*
270	*	*	736	675	583	507	473	522	628	*	*	705	*	*
275	*	*	738	678	589	515	481	529	633	*	*	706	*	*
280	*	*	740	682	596	523	489	536	638	*	*	707	*	*
285	*	*	742	685	603	532	497	544	643	*	*	*	*	*
290	*	*	742	688	611	542	506	553	648	*	*	*	*	*
295	*	*	742	691	619	552	515	562	654	*	*	*	*	*
300	*	*	742	694	627	563	526	572	659	*	*	*	*	*
310	*	*	*	699	644	584	549	594	669	*	*	707	*	*
320	*	*	*	704	660	606	575	617	679	*	*	708	*	*
330	*	*	*	707	674	628	602	640	687	*	*	711	*	*
340	*	*	*	710	686	649	627	659	694	*	*	714	*	*
350	*	*	*	714	697	667	650	675	701	*	*	718	*	*
360	*	*	*	717	706	681	669	688	706	*	*	723	*	*
370	*	*	*	720	712	692	682	695	709	*	*	727	*	*
380	*	*	*	724	717	701	692	700	712	*	*	730	*	*
390	*	*	*	727	721	708	700	703	713	*	*	733	*	*
400	*	*	*	731	724	715	707	710	*	*	*	736	*	*

*Measurement not reliable

TABLE 3C-1 CONCRETE TEMPERATURES MEASURED WITH THERMOCOUPLES IN FRAME C

Time (min)	Temperature (°C) Measured at Thermocouple No:													
	39	40	41	42	43	44	45	46	47	48	49	50	51	52
0	16	*	17	16	16	16	16	16	16	16	16	17	17	17
5	168	*	59	33	20	17	16	17	21	35	81	122	199	272
10	290	*	113	74	28	18	17	18	31	88	159	232	358	453
15	379	*	167	107	42	21	17	22	64	125	237	335	469	561
20	448	*	213	137	104	27	19	35	93	161	307	416	547	634
25	506	*	257	173	107	47	24	63	107	215	370	482	605	686
30	559	*	299	206	*	55	32	73	107	261	426	535	651	727
35	599	*	337	239	*	62	41	79	116	302	473	576	684	756
40	630	*	371	268	*	70	51	84	132	340	513	607	711	780
45	655	*	401	295	116	79	64	92	151	372	544	635	733	802
50	675	*	427	319	130	95	79	100	171	400	570	658	752	821
55	693	*	449	341	144	102	100	102	192	425	591	677	771	838
60	707	*	469	359	158	103	103	104	212	446	609	694	788	852
65	721	*	486	376	171	104	104	113	232	465	625	709	803	865
70	733	*	502	391	185	113	105	121	250	482	640	723	817	876
75	745	*	516	406	199	120	106	129	268	497	653	736	829	888
80	756	*	528	419	213	128	107	137	286	511	666	747	840	898
85	768	*	540	432	228	138	109	147	302	523	677	758	849	908
90	779	*	551	444	243	149	116	158	318	534	688	769	857	918
95	791	*	561	456	257	159	122	169	334	545	698	780	866	929
100	801	*	571	468	271	170	127	181	349	555	708	790	873	940
105	811	*	581	479	284	180	135	193	363	564	716	799	880	949
110	817	*	590	490	298	191	143	206	377	574	725	806	884	952
115	825	*	598	500	311	202	153	219	390	582	732	813	889	958

*Measurement not reliable

TABLE 3C-2 CONCRETE TEMPERATURES MEASURED WITH THERMOCOUPLES IN FRAME C

Time (min)	Temperature (°C) Measured at Thermocouple No: 39	40	41	42	43	44	45	46	47	48	49	50	51	52
120	832	*	606	510	324	213	163	232	403	590	740	819	896	964
125	838	*	614	520	337	225	175	245	416	598	747	826	902	968
130	844	*	621	529	350	237	187	258	428	606	753	831	908	971
135	*	*	627	537	362	250	200	271	440	613	759	834	908	*
140	*	*	633	544	374	262	213	284	452	620	763	836	908	*
145	846	*	638	552	386	275	226	297	463	627	768	838	910	*
150	849	*	643	558	397	287	238	309	474	632	773	841	913	*
155	854	*	648	565	408	299	250	322	484	638	777	844	917	*
160	858	*	654	571	418	310	262	333	494	644	781	847	921	*
165	861	*	659	577	428	322	274	345	503	649	785	851	925	974
170	865	*	664	583	438	333	286	356	511	654	789	853	930	978
175	868	*	669	589	447	343	297	366	520	659	793	857	934	980
180	872	*	674	595	457	354	308	377	527	664	796	860	939	984
185	873	*	678	601	465	364	319	387	535	669	800	864	941	984
190	875	*	683	606	474	374	330	396	542	673	802	866	943	984
195	879	*	687	611	482	384	340	406	549	677	805	869	947	991
200	884	*	691	616	490	393	350	415	555	681	808	872	951	996
205	887	*	696	621	498	403	360	424	561	685	812	876	955	999
210	891	*	700	626	505	412	370	433	567	689	815	880	959	1003
215	895	*	705	631	513	420	379	441	573	693	819	884	964	1007
220	899	*	709	636	520	429	388	449	578	697	823	889	968	1011
225	903	*	713	641	527	438	397	457	583	701	827	894	972	1015
230	906	*	717	645	535	446	406	465	588	705	830	898	976	1018
235	912	*	721	650	542	455	415	473	593	709	834	902	982	1025

*Measurement not reliable

TABLE 3C-3 CONCRETE TEMPERATURES MEASURED WITH THERMOCOUPLES IN FRAME C

Time (min)	Temperature (°C) Measured at Thermocouple No:													
	39	40	41	42	43	44	45	46	47	48	49	50	51	52
240	915	*	725	654	550	463	424	480	597	713	838	907	987	1030
245	917	*	729	658	559	472	433	487	602	718	841	912	991	1033
250	919	*	732	662	568	481	444	494	607	722	844	916	995	1038
255	920	*	734	666	577	491	455	501	611	726	847	921	999	1042
260	*	*	736	670	587	501	467	507	616	730	849	925	1002	1045
265	*	*	737	674	598	513	480	514	621	733	850	929	1003	1045
270	*	*	*	677	608	526	494	521	625	737	850	931	*	1046
275	*	*	*	681	619	540	510	528	630	740	*	933	*	*
280	*	*	*	684	629	555	527	536	635	742	*	933	*	*
285	*	*	*	687	639	570	545	544	641	744	*	*	*	*
290	*	*	*	690	648	586	563	553	646	745	*	*	*	*
295	*	*	*	693	656	601	581	563	651	745	*	*	*	*
300	*	*	*	696	665	616	599	575	657	*	*	*	*	*
310	*	*	*	702	679	642	630	599	667	*	*	*	*	*
320	*	*	*	708	691	662	654	625	677	*	*	*	*	*
330	*	*	*	712	701	678	672	647	684	*	*	*	*	*
340	*	*	*	717	736	690	686	665	690	*	*	*	*	*
350	*	*	*	723	*	700	696	679	694	*	*	*	*	*
360	*	*	*	727	*	708	704	689	698	*	*	*	*	*
370	*	*	*	731	*	714	710	695	700	*	*	*	*	*
380	*	*	*	735	*	719	716	701	703	*	*	*	*	*
390	*	*	*	740	*	725	722	707	707	*	*	*	*	*
400	*	*	*	745	741	733	728	713	712	*	*	*	*	*

*Measurement not reliable

TABLE 3D-1 CONCRETE TEMPERATURES MEASURED WITH THERMOCOUPLES IN FRAME D

Time (min)	Temperature (°C) Measured at Thermocouple No:											
	53	54	55	56	57	58	59	60	61	62	63	64
0	7	7	7	7	7	8	8	7	7	7	7	7
5	137	93	41	22	11	9	8	9	12	27	69	113
10	245	172	97	57	20	10	9	10	23	83	148	217
15	332	245	136	99	36	13	10	15	60	123	224	318
20	404	308	178	119	78	20	12	24	85	153	294	400
25	468	364	221	152	99	51	19	38	98	196	358	467
30	524	416	263	184	101	64	30	52	108	243	414	524
35	564	459	301	215	104	70	39	65	124	286	465	571
40	594	493	334	244	109	75	48	79	143	324	507	606
45	620	522	364	270	117	79	57	101	165	359	542	634
50	642	546	389	291	125	87	68	103	186	389	569	656
55	660	564	402	*	126	96	84	106	207	415	591	674
60	673	575	408	*	128	107	106	112	228	437	609	689
65	685	589	434	330	149	109	110	121	249	457	625	703
70	700	605	456	354	170	111	111	130	268	474	639	715
75	714	620	474	372	186	118	111	138	288	490	651	726
80	727	632	490	388	201	125	112	146	306	504	663	736
85	738	644	504	403	215	132	114	155	323	516	673	747
90	750	655	517	416	229	141	121	165	340	529	684	759
95	760	665	528	429	242	150	127	175	355	541	694	771
100	770	675	539	441	256	159	133	186	370	552	704	782
105	779	683	549	453	269	169	140	197	384	563	714	792
110	786	691	559	464	282	180	148	209	397	573	722	800
115	794	698	569	475	295	192	156	221	410	582	730	807

*Measurement not reliable

TABLE 3D-2 CONCRETE TEMPERATURES MEASURED WITH THERMOCOUPLES IN FRAME D

Time (min)	Temperature (°C) Measured at Thermocouple No:											
	53	54	55	56	57	58	59	60	61	62	63	64
120	801	705	576	485	309	204	164	234	423	591	738	814
125	807	712	584	496	322	216	172	247	435	600	746	821
130	813	717	592	506	335	228	182	260	447	608	753	827
135	*	721	600	516	348	241	194	272	459	616	760	831
140	815	724	606	524	361	253	207	285	470	623	765	833
145	818	729	613	533	373	266	220	297	480	630	770	836
150	823	733	619	541	385	278	233	309	490	636	774	839
155	827	738	625	548	397	291	246	321	499	642	779	842
160	832	743	631	556	407	303	258	332	508	648	783	846
165	836	748	637	563	418	315	270	343	517	653	788	849
170	840	753	643	569	429	326	283	354	525	658	792	853
175	844	758	648	576	439	337	295	364	533	663	796	856
180	849	762	654	582	448	348	306	375	540	668	801	860
185	851	766	659	588	458	359	317	385	547	673	805	863
190	853	769	663	594	467	369	328	394	554	677	809	865
195	857	773	668	599	475	379	339	404	561	682	813	867
200	862	778	673	604	483	389	349	413	567	686	817	871
205	866	782	677	609	491	398	359	422	573	690	821	875
210	871	787	682	614	498	407	368	431	579	695	824	878
215	875	791	687	619	506	416	378	439	584	699	828	882
220	880	796	692	624	513	425	387	448	590	703	831	886
225	885	800	696	629	519	433	395	456	595	707	835	890
230	889	805	701	634	526	441	404	464	600	711	839	895
235	895	809	705	639	532	449	413	472	605	715	842	900

*Measurement not reliable

TABLE 3D-3 CONCRETE TEMPERATURES MEASURED WITH THERMOCOUPLES IN FRAME D

Time (min)	Temperature (°C) Measured at Thermocouple No:											
	53	54	55	56	57	58	59	60	61	62	63	64
240	901	814	710	643	538	457	421	480	610	719	846	905
245	905	819	714	648	543	465	429	489	614	723	850	910
250	911	823	719	652	549	472	438	497	619	727	854	914
916	916	827	723	657	554	480	447	506	624	731	857	919
260	920	831	727	661	559	487	456	515	629	735	860	923
265	924	834	731	666	564	494	465	524	634	738	863	926
270	928	837	735	670	569	501	475	534	638	742	864	929
275	930	839	738	673	573	509	485	545	643	746	866	932
280	932	841	741	677	578	517	496	555	648	749	866	933
285	933	843	744	680	583	525	507	567	653	753	866	934
290	934	843	746	684	588	534	520	578	658	756	866	934
295	*	843	748	687	593	543	533	589	663	758	*	*
300	*	*	750	689	598	553	547	599	669	761	*	*
310	*	*	751	694	609	576	577	619	679	763	*	*
320	*	*	751	697	622	599	606	637	688	*	*	*
330	*	*	*	700	637	623	632	651	696	*	*	*
340	*	*	*	703	651	644	654	664	704	*	*	*
350	*	*	*	706	664	662	671	676	710	*	*	*
360	*	*	*	709	675	676	684	685	714	*	*	*
370	*	*	*	713	684	687	694	692	718	*	*	*
380	*	*	*	717	692	696	703	698	722	*	*	*
390	*	*	*	722	700	705	711	703	727	*	*	*
400	*	*	*	728	708	714	719	708	731	*	*	*

*Measurement not reliable

TABLE 4 AVERAGE FURNACE TEMPERATURE

Time (min)	Temperature (°C)	Time (min)	Temperature (°C)	Time (min)	Temperature (°C)
0	13	120	1029	240	1083
5	596	125	1030	245	1087
10	693	130	1035	250	1095
15	741	135	1019	255	1100
20	780	140	1022	260	1104
25	818	145	1022	265	1108
30	841	150	1025	270	1111
35	860	155	1030	275	1113
40	875	160	1032	280	1115
45	896	165	1036	285	1120
50	908	170	1037	290	1123
55	925	175	1041	295	1128
60	934	180	1043	300	1130
65	942	185	1038	310	1136
70	948	190	1037	320	1141
75	957	195	1045	330	1112
80	967	200	1049	340	1148
85	975	205	1052	350	1168
90	984	210	1056	360	1175
95	992	215	1058	370	1180
100	1002	220	1064	380	1187
105	1016	225	1068	390	1188
110	1018	230	1067	400	1199
115	1027	235	1078		

TABLE 5 MEASURED AXIAL DEFORMATION OF COLUMN

Time (min)	Deformation (mm)	Time (min)	Deformation (mm)	Time (min)	Deformation (mm)
0	0	180	10.9	360	-4.3
5	0.4	185	10.8	365	-4.8
10	1.2	190	10.6	370	-5.2
15	2.4	195	10.5	375	-5.7
20	3.6	200	10.3	380	-6.2
25	4.3	205	10.1	385	-6.6
30	4.5	210	9.9	390	-7.2
35	4.8	215	9.6	395	-7.7
40	5.1	220	9.4	400	-8.2
45	5.5	225	9.1	405	-8.6
50	5.8	230	8.9	410	-9.1
55	6.4	235	8.5	415	-9.5
60	6.9	240	8.2	420	-10.0
65	7.3	245	7.8	425	-10.4
70	7.8	250	7.4	430	-10.9
75	8.2	255	7.0	435	-11.5
80	8.6	260	6.5	440	-12.1
85	9.0	265	6.0	445	-12.6
90	9.3	270	5.5	450	-13.2
95	9.7	275	5.0	455	-13.8
100	10.0	280	4.4	460	-14.7
105	10.3	285	3.9	465	-15.5
110	10.5	290	3.3	470	-16.3
115	10.7	295	2.8	475	-17.2
120	10.8	300	2.2	480	-18.2
125	10.9	305	1.6	485	-19.1
130	11.0	310	1.1	490	-20.1
135	11.1	315	0.5	495	-21.3
140	11.1	320	-0.1	500	-22.7
145	11.1	325	-0.6	505	-24.2
150	11.1	330	-1.2	510	-26.0
155	11.1	335	-1.7		
160	11.1	340	-2.2		
165	11.1	345	-2.8		
170	11.1	350	-3.3		
175	11.1	355	-3.8		

(-) sign indicates contraction of column past initial starting position

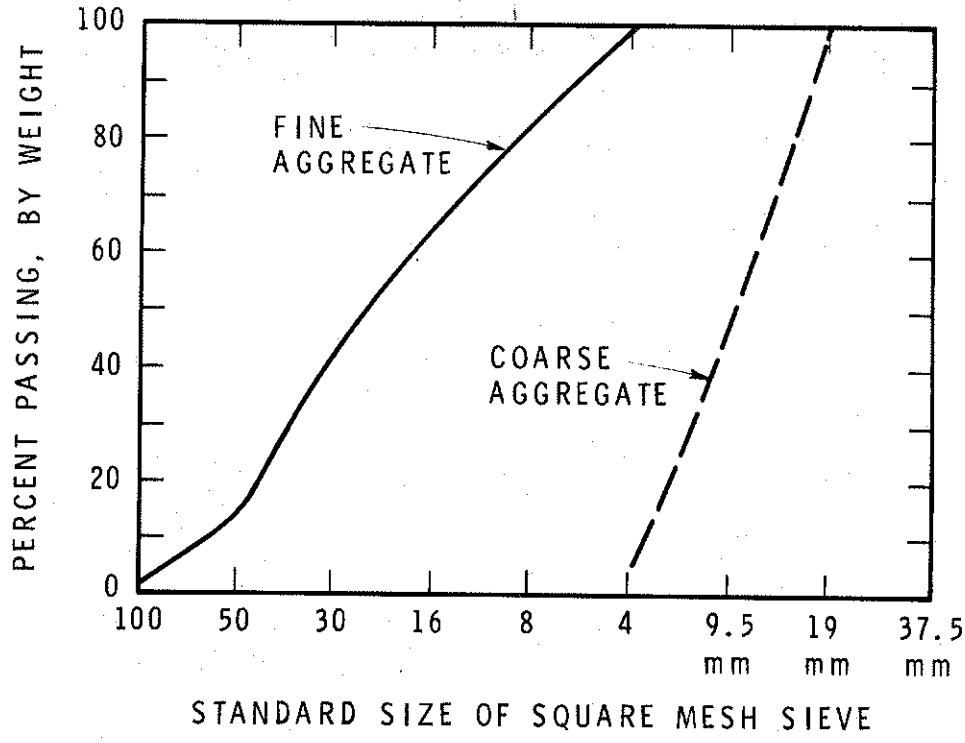


FIGURE 1

GRADATION CURVES OF CARBONATE AGGREGATE

BR 6444-1

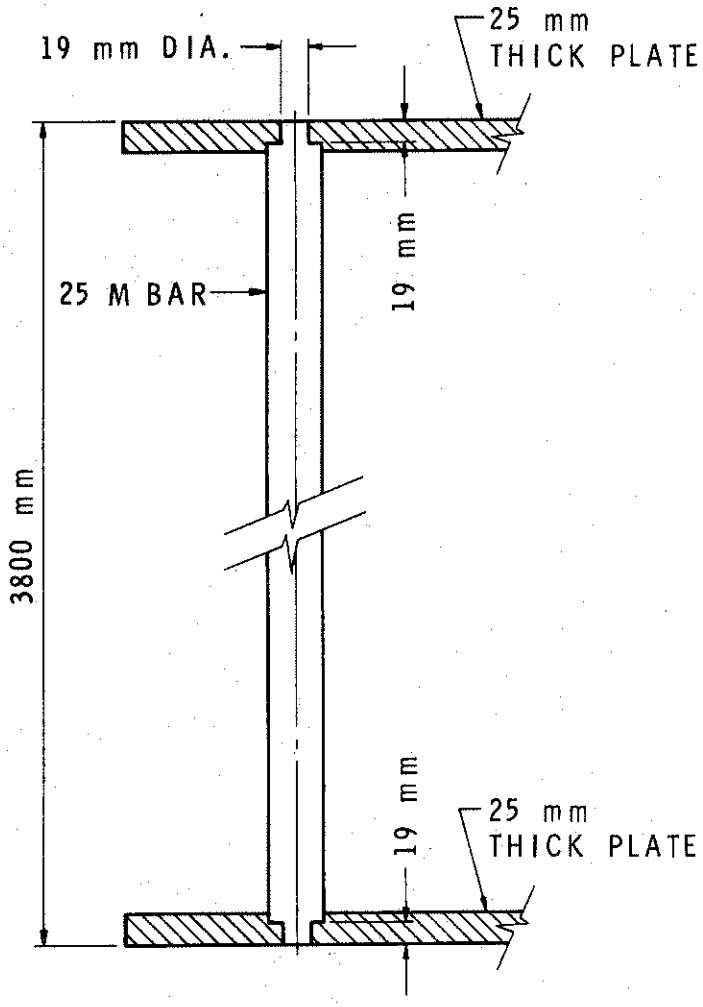


FIGURE 2

MAIN REINFORCING BARS

BR 6432-2

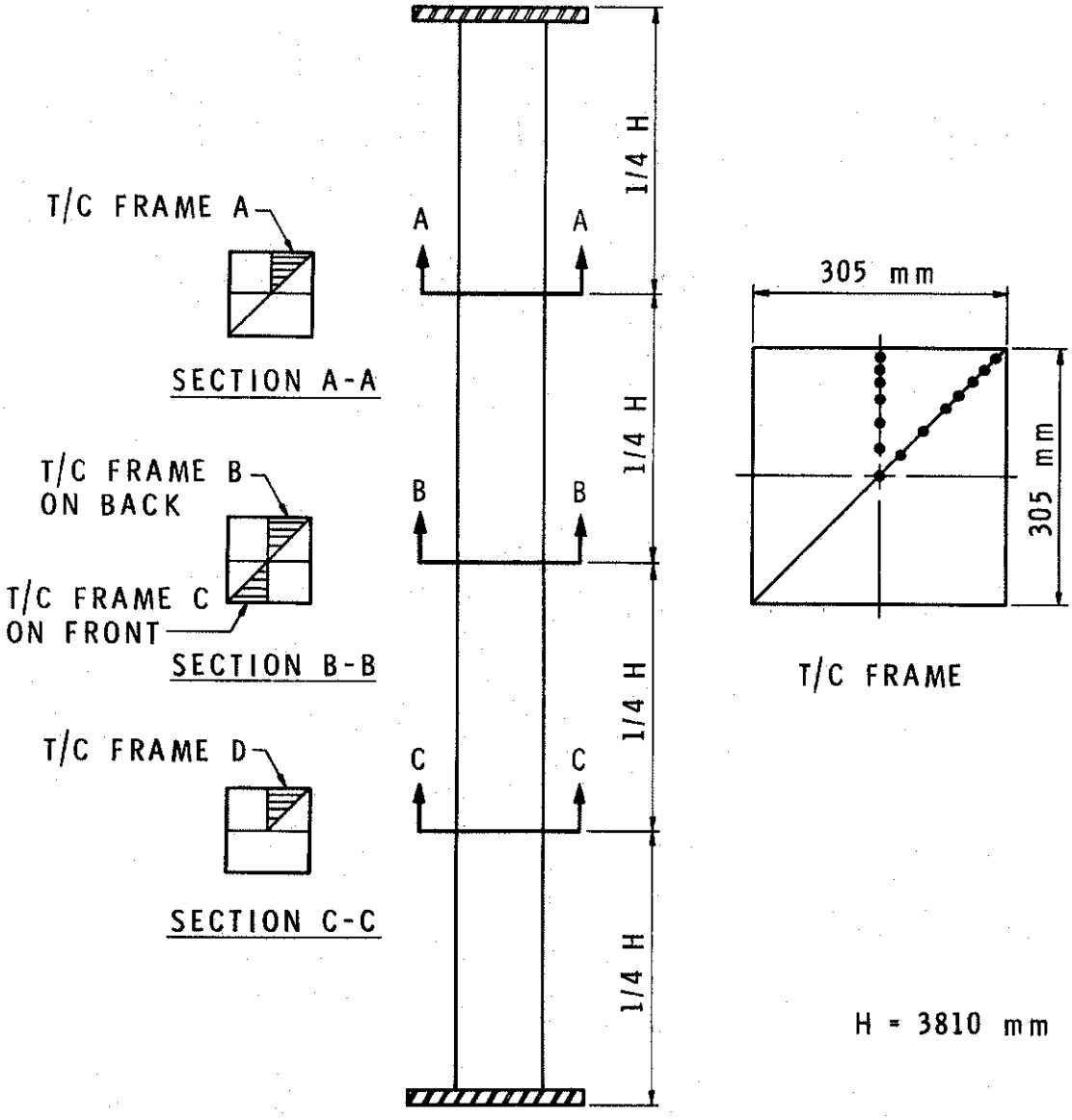


FIGURE 3

LAYOUT OF THERMOCOUPLE FRAMES

BR 6432-3

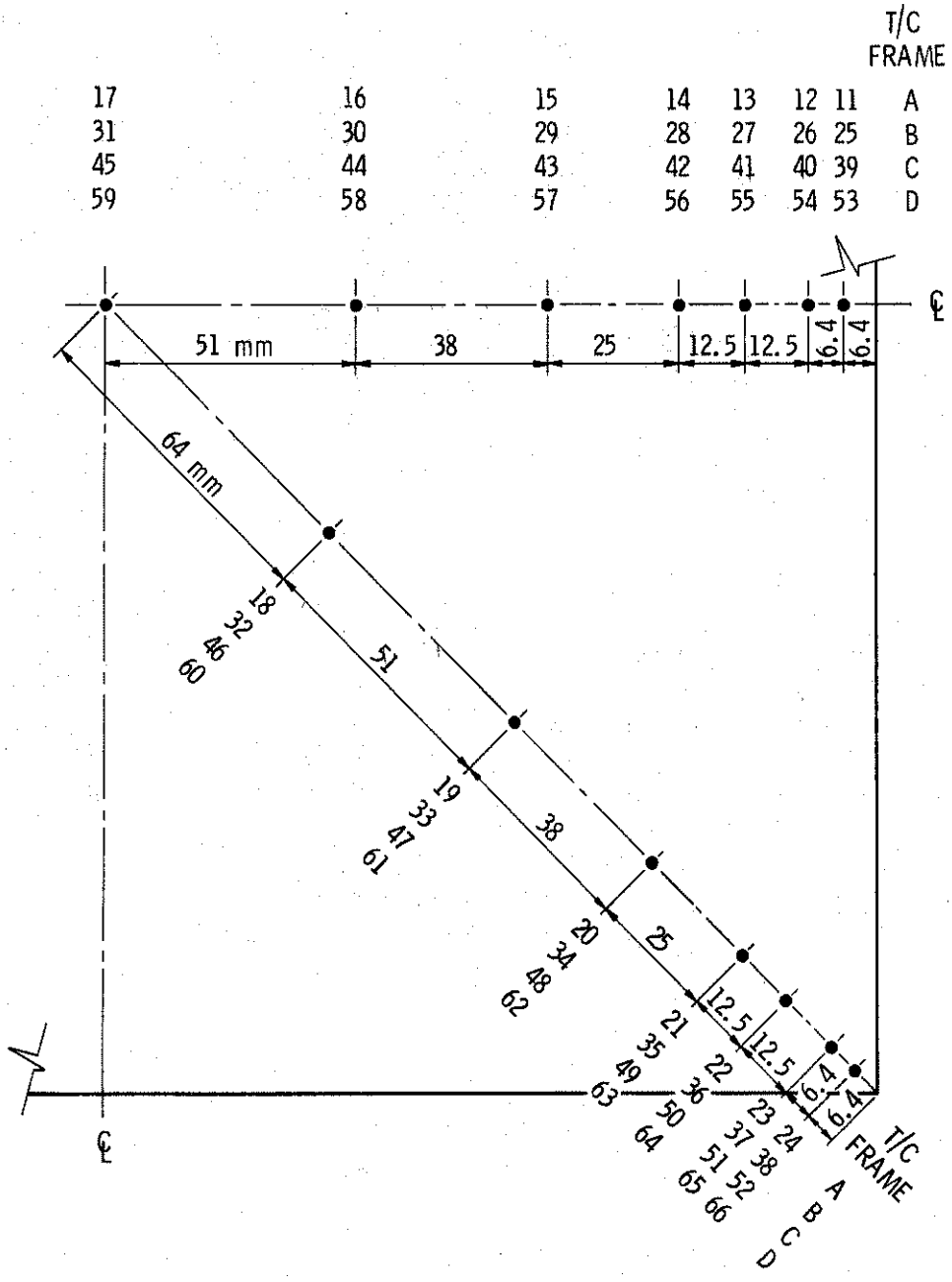


FIGURE 4

LOCATION AND NUMBERS OF THERMOCOUPLES IN A SECTION

BR 6432-4

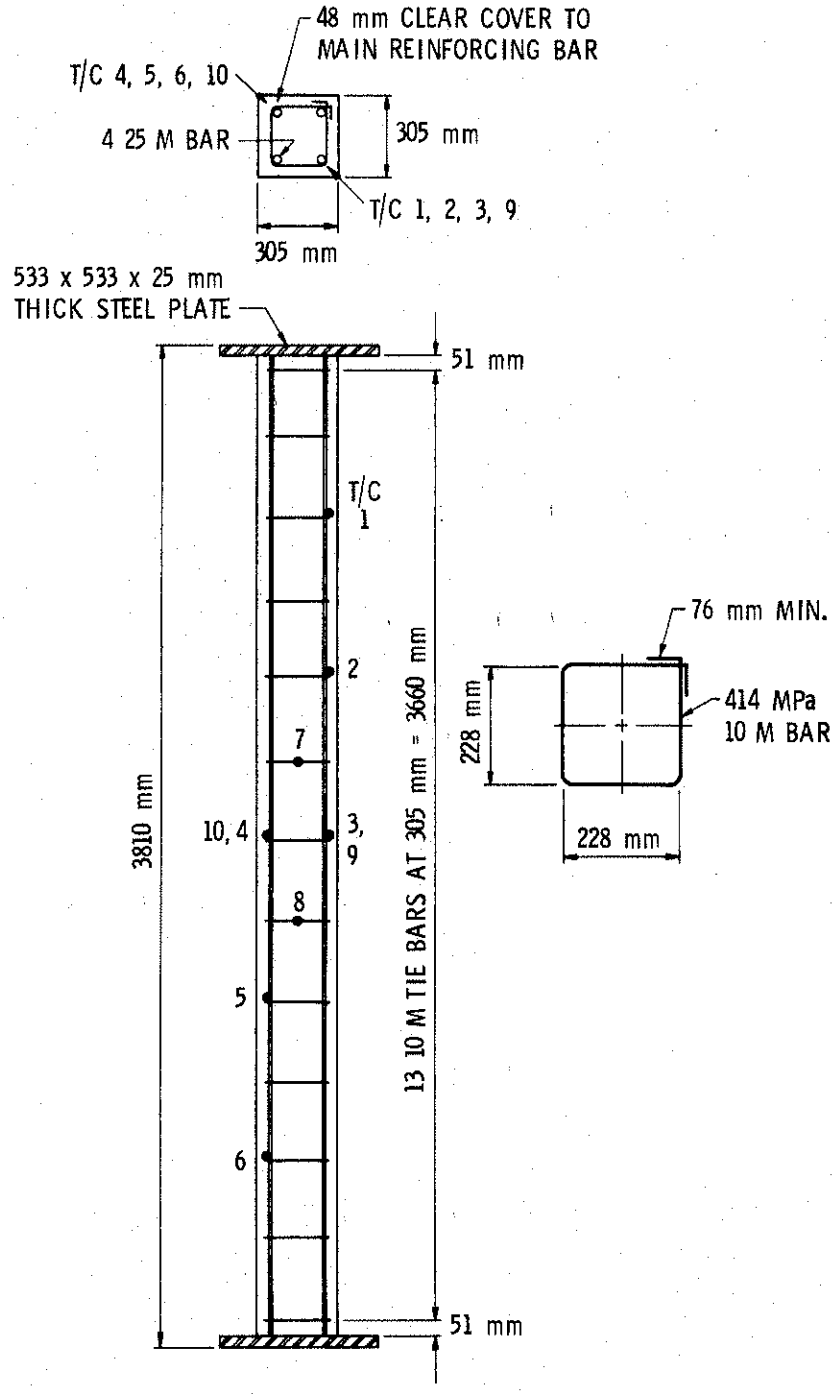


FIGURE 5

THERMOCOUPLES ON REINFORCING BARS

BR 6432-5

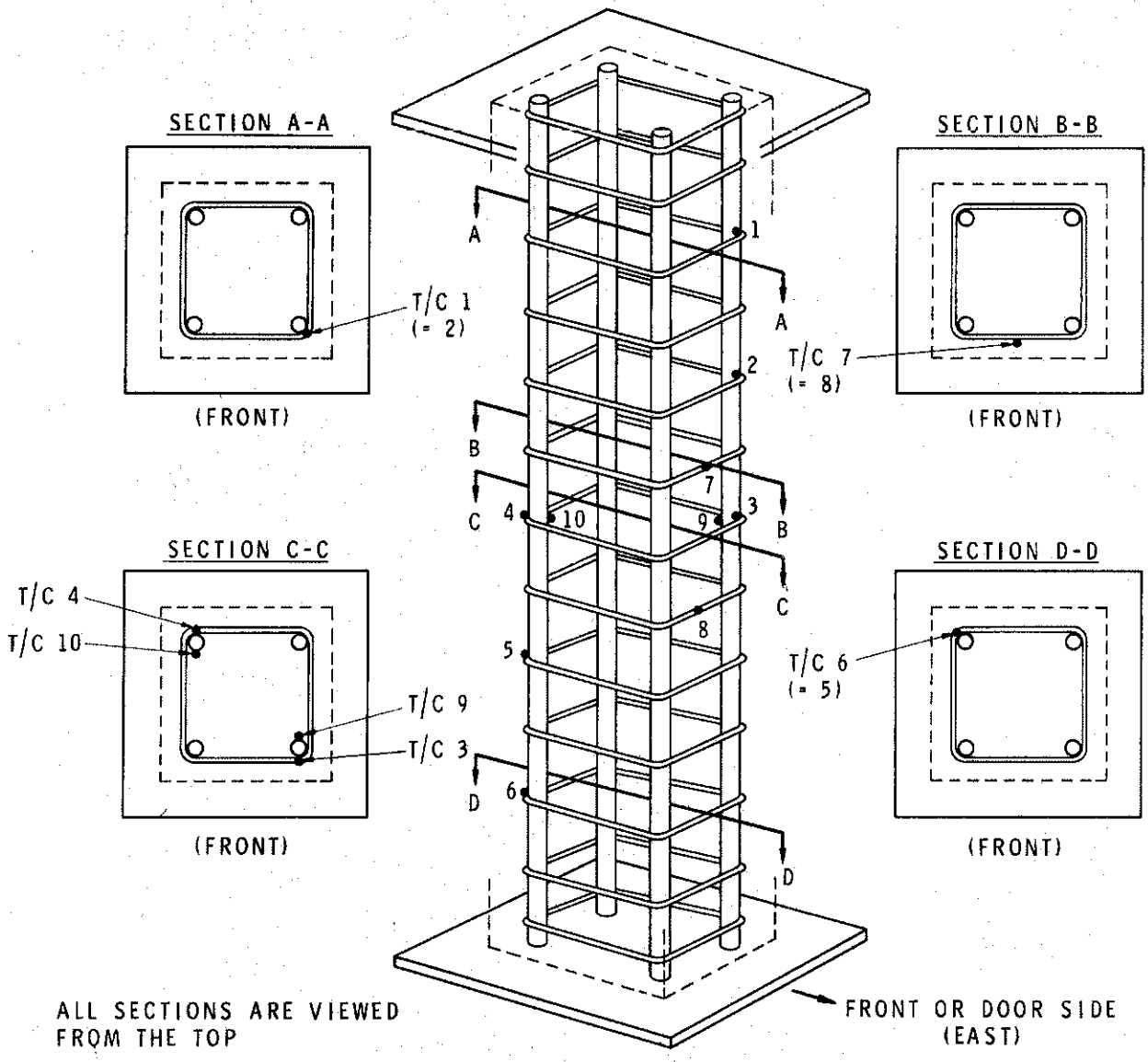


FIGURE 6

THERMOCOUPLES ON REINFORCING BARS (305 mm x 305 mm COLUMN)

BR 6432-6

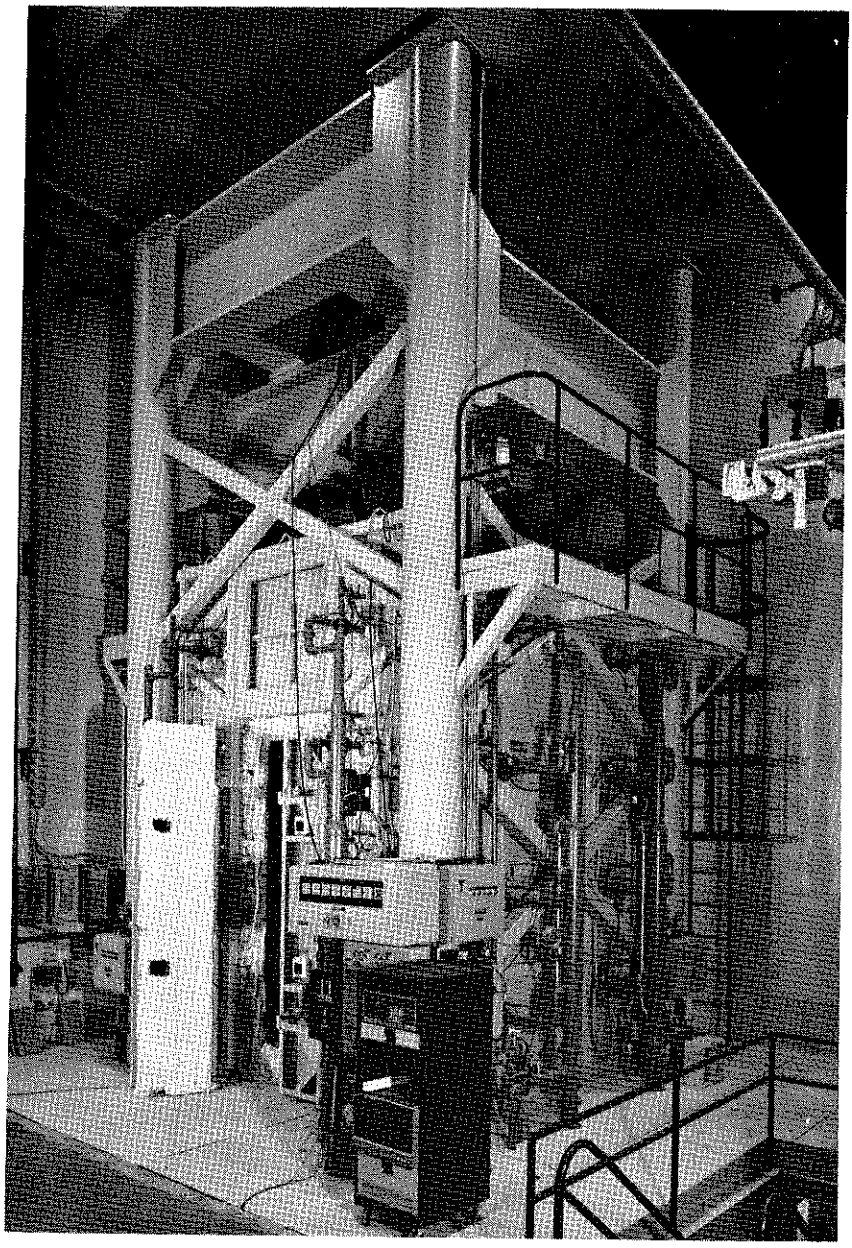
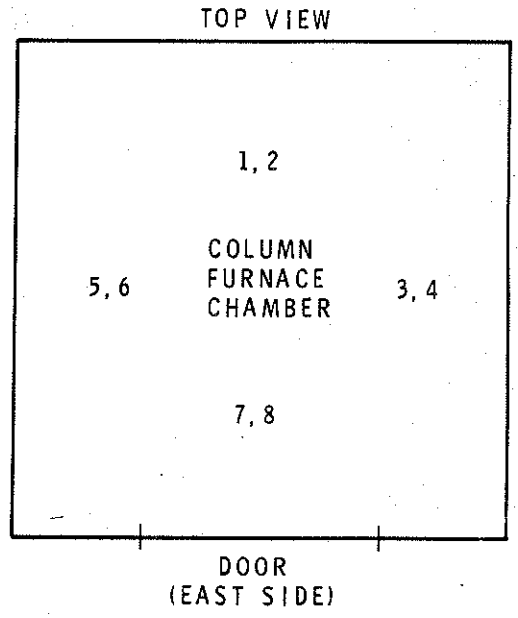


FIGURE 7

TEST FURNACE



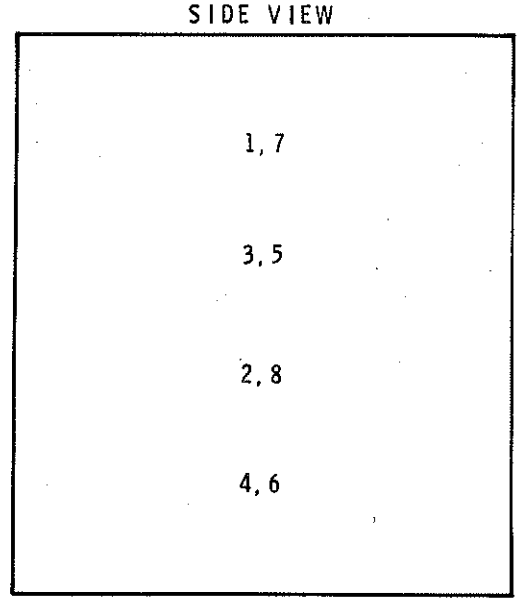


FIGURE 8

LOCATION AND NUMBERS OF THERMOCOUPLES IN COLUMN FURNACE CHAMBER

BR 6432-7

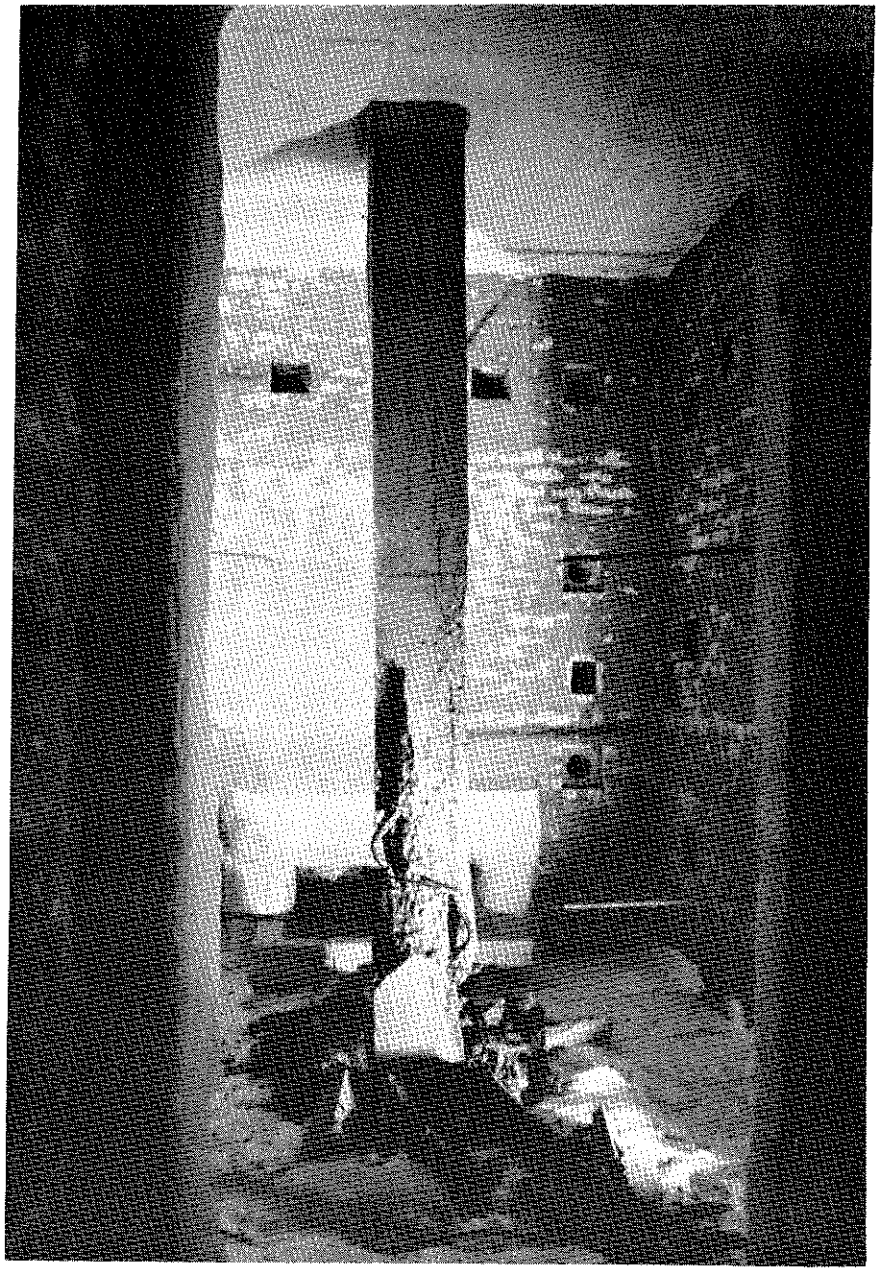


FIGURE 9

COLUMN TEST SPECIMEN NO. 10 AFTER TEST

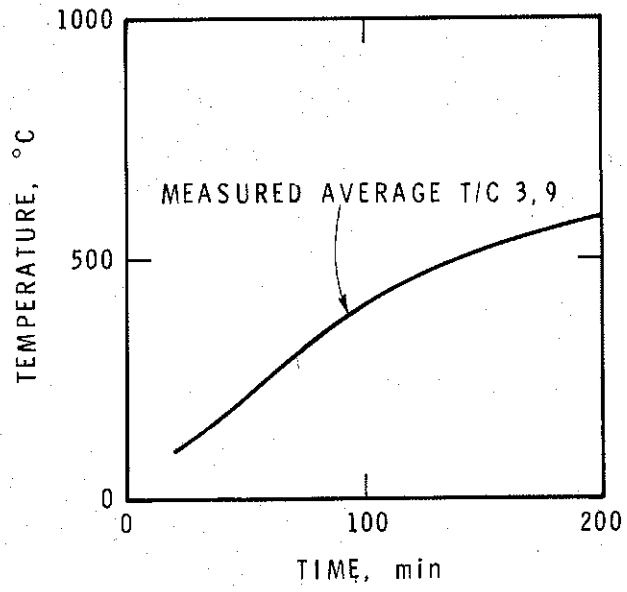


FIGURE 10

MEASURED AVERAGE TEMPERATURES ON MAIN REINFORCING BARS

BR 6444-2

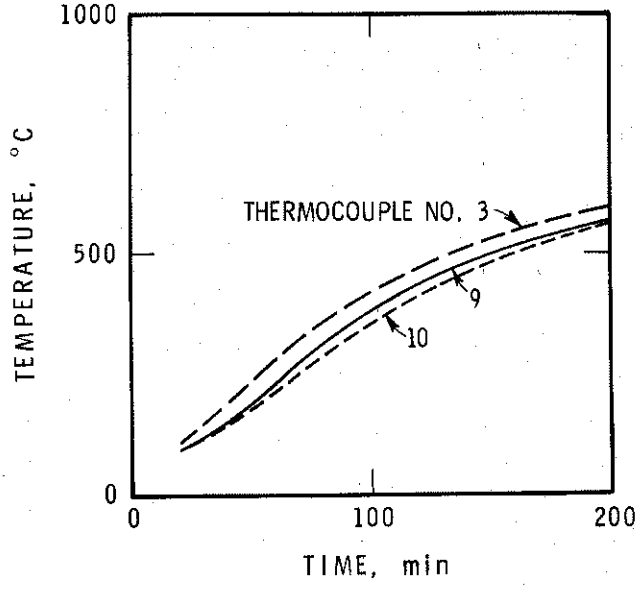


FIGURE 11

TEMPERATURES MEASURED ON MAIN REINFORCING BARS

BR 6444-3