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Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20358628
Internal Report (National Research Council of Canada. Institute for Research in Construction), 1991-12

National Research Council Canada
Institute for Research in Construction

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Internal Report No. 619

Date of issue: December 1991

This is an internal report of the Institute for Research in Construction. Although not intended for general distribution, it may be cited as a reference in other publications

Canada

FIRE RESISTANCE TEST OF A SQUARE REINFORCED CONCRETE COLUMN

by

J. Myllymäki and T. T. Lie

ABSTRACT

The results of a fire resistance test conducted at NRC on a reinforced concrete column, made by the Technical Research Centre of Finland (VTT), are described. The test was carried out as a part of a study on concrete-filled steel columns to determine the influence of the steel encasing on the fire resistance of the column. This influence can be assessed by comparing the results with those obtained for a similar column with steel encasing. The dimensions of the tested column were 300 mm × 300 mm × 3810 mm and it was constructed of Finish siliceous aggregate concrete.

1. INTRODUCTION

For a number of years, the National Research Council of Canada (NRC) and the Technical Research Centre of Finland (VTT) have independently been engaged in studies to predict the fire resistance of concrete filled steel columns. The mutual interest in these studies led to an agreement between NRC and VTT to conduct joint studies on the fire resistance of concrete-filled steel columns. These studies include theoretical as well as experimental studies.

As a part of these studies, a reinforced concrete column without steel encasing was tested to obtain information on the influence of the steel encasing on the fire resistance of the column. This influence can be assessed by comparing the fire resistance of the bare reinforced concrete column with the fire resistance of similar reinforced concrete columns with steel encasing, tested earlier for VTT at the University of Braunschweig in Germany [1].

In this report, the results of a test, conducted at NRC, on the reinforced concrete column without steel encasing are described. The column was designed by the Fire Technology Laboratory and fabricated by the Building Materials Laboratory of VTT in Finland. It was tested at the National Fire Laboratory of the Institute for Research in Construction, NRC.

2. TEST SPECIMEN

One reinforced concrete column (300 mm × 300 mm × 3810 mm) was constructed and tested under a concentric load. Details of the test specimens are given in Table 1 and illustrated in Fig. 1. Further details of the test specimen and its fabrication are given below.

2.1 Dimensions

The column was 3810 mm long from end plate to end plate. The cross section of the column was 300 × 300 mm. The column had 24 mm cover to the 6 mm dia. tie bars and 20 mm cover to the 10 mm dia. tie bars. The cover to the vertical main bars was 30 mm.

2.2 Materials

Steel:

The column end plates consisted of steel meeting the requirements of Finnish Standard SFS 200 grade Fe 52 C [2].

Weldable ribbed bars meeting the requirements of Standard SFS 1215 grade A 500 HW [3] were used for the main and tie bars. The diameter of the longitudinal steel bars in the column was 16 mm. The diameters of the ties were 6 and 10 mm. A tensile test was performed for each bar size to determine yield and ultimate strength. The test results are listed in Table 2.

Cement:

The concrete mix was poured in the Building Materials Laboratory of the Technical Research Centre of Finland. In the pour, a general purpose portland cement for construction of concrete structures was used. The cement was manufactured by Oy Partek Ab.

Aggregate:

The aggregate used was Finnish siliceous sand and gravel, both from Lohja Oy Rudus. A sieve analysis was conducted. The results of the sieve analysis are given in Table 3.

Concrete Mix:

Batch quantities for the mix are given in Table 3. The mix contained a super plasticizer called SP 62. The average 28-day concrete cube strength was 37.5 MPa.

2.3 Fabrication

The column was cast in vertical forms made of smooth plywood.

Steel Plates and Reinforcing Bars:

The column length was 3810 mm measured from end plate to end plate. The longitudinal 16 mm reinforcement bars were cut to 3790 mm.

The dimensions of the end plates were 508 × 610 × 40 mm. Holes with a diameter 4 mm larger than the diameter of the longitudinal reinforcing bars were drilled through the plates.

The main bars and ties were joined together to complete the steel cage. The steel cage was then placed vertically into the form on a levelled end plate in such a way that the ends of the bars were positioned in the holes.

The bottom steel end plate and the bars were then welded. Centering and perpendicularity of the end plates were given special attention. A fillet weld was made around the bars on the outer face of the bottom plate. The type of welding rod used was OK Autrod 12.51, which has a tensile strength of 400 MPa. The rough surfaces of the welds 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 column. Before positioning the top plate, a 20 mm layer of mortar was spread over the top of the column to ensure good contact between the steel plate and concrete. The mortar, called Rapid Set Grout, was non-shrinkable high strength mortar, which had a compressive strength of 84.4 MPa at 28 days. Using the same procedure as for the bottom plate, the top plate was welded on the outer side of the bars and smoothed.

Concrete Placement:

The concrete was mixed in a paddle mixer, called Zyklos. A concrete placement bucket and a long plastic tube were used to deposit the mix in the steel column. When necessary, an internal vibrator was carefully applied to consolidate the concrete. To avoid possible moisture leaks, the column was sealed at the top end with a plastic sheet and tape before and after the welding of the top plate.

Curing:

After 20 days, the forms were stripped and the column conditioned in an atmosphere controlled at about 20°C and 30% relative humidity.

Thermocouples:

Type K chromel-alumel thermocouples, with a thickness of 0.5 mm, were used for measuring concrete and reinforcement temperatures at several locations in different cross sections of the columns. At each level, some of the thermocouples in the concrete were tied to steel rods that were firmly secured to the main reinforcing bars. The temperatures were measured at approximately one-quarter height, mid-height and three-quarters height. At mid-height, the temperatures were measured along the whole length of an axis and a diagonal of the section; at the other two levels, the temperatures were measured only in the middle of the section and at the surface of the section. The steel temperatures were also measured at various locations. The locations of the thermocouple levels in the column are shown in Fig. 2. The location of the thermocouples at various levels is shown in Fig. 3.

3. MATERIAL PROPERTIES TESTS

3.1 Cube Compressive Strength

From the concrete mix, ten 150 mm cubes were made using steel forms. Compression strength tests were conducted for three specimens at 7 and 28 days and on the test date. The tests were conducted according to Finnish Standard SFS 4474 [4] (ISO 4012).

3.2 Thermal Properties

From the concrete mix, ten 100 × 200 × 50 mm prisms were made, using wooden forms. Details concerning the thermal properties measurements are given in the Appendix. Values of the measured properties as a function of temperature are given in Figs. A1-A4 and Tables A1-A4 in the Appendix.

3.3 Cylinder Compressive Strength and Moisture Content

From the concrete mix, a short column was constructed. The size of the column was 300 × 300 × 600 mm. On the test date, two cylinders with a diameter and height of 100 mm were cut from the concrete, using a core drill. The cylinders were used for the measurement of the strength of the concrete.

4. 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 produces 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. 4). The characteristics and instrumentation of the furnace are described in detail in Ref. [5]. Only a brief description of the furnace and the main components is given here.

4.1 Loading Device

A hydraulic jack with a capacity of 9778 kN produces a load (N_1) along the axis of the test column (Fig. 5). The jack is located at the bottom of the furnace chamber. Eccentric loads can be applied by means of hydraulic jacks (N_2), one at the top and one at the bottom of the column, located at a distance of 508 mm from the axis of the column. The capacity of the top jack is 587 kN and that of the bottom jack 489 kN.

4.2 Furnace Chamber

The furnace chamber has a floor area of 2642 × 2642 mm and is 3048 mm high. The interior faces of the chamber are lined with insulating materials that efficiently transfer heat 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. Each burner can be adjusted individually, which allows for a high degree of temperature uniformity in the furnace chamber. The pressure in the furnace chamber is also adjustable and was set somewhat lower than atmospheric pressure.

4.3 Instrumentation

The furnace temperatures were measured with the aid of eight chromel-alumel thermocouples. The thermocouple junctions were located 305 mm from the test specimen at various heights. Two thermocouples were placed opposite each other at intervals of 610 mm along the height of the furnace chamber. The locations of their junctions and their numbering are shown in Fig. 6. Thermocouples 4 and 6 were located at a height of 610 mm from the floor, Thermocouples 2 and 8 at 1220 mm, Thermocouples 3 and 5 at 1830 mm and Thermocouples 1 and 7 at 2440 mm. The temperatures measured by the thermocouples were averaged automatically and the average temperature used as the criterion for controlling the furnace temperature.

The loads were controlled by servocontrollers and measured with pressure transducers. The accuracy of controlling and measuring loads is about 4 kN at lower load levels and relatively better at higher loads.

The lateral deflection of the column at mid-height was measured using a theodolite. The axial deformation of the test column was determined by measuring the displacement of the jack that supports the column. The rotation of the end plates of the column was determined by measuring the displacement of the plates at a distance of 711 mm from the centre of the hinge at the top and at a distance of 1295 mm from the centre of the hinge at the bottom. The displacements were measured using transducers with an accuracy of 0.002 mm.

5. TEST CONDITIONS AND PROCEDURE

The column was tested with both ends hinged. The column was installed in the furnace by securing the end plates to the plates of the bearings (Fig. 5). The bearings were bolted to a loading head at the top and to the plate of the main hydraulic jack at the bottom.

Before the test, the moisture condition in the centre of a column section was measured by inserting a Vaisala moisture sensor in a hole drilled in the concrete at a height of 380 mm above the bottom of the column. The readings are given in Section 6.

5.1 Loading

The column was subjected to a concentric load of 1400 kN. The load was applied approximately 45 minutes before the start of the test. At that stage, a condition was reached at which no further increase of the axial deformation of the column could be measured. This condition was selected as the initial condition of the column deformations.

5.2 Fire Exposure

During the test, the column was exposed to heating controlled in such a way that the average temperature in the furnace followed, as closely as possible, the ISO 834 [6] standard temperature-time curve. This curve can be given by the following equation:

$$T_f - T_o = 345 \log_{10} (8t + 1)$$

where:
- t = time in minutes
- T_f = temperature of furnace in °C
- T_o = initial furnace temperature in °C

During the test, temperatures in the furnace and in the column were measured at the locations described earlier.

5.3 Recording of Results

Temperature readings were taken at each thermocouple location at intervals of two minutes. The axial deformation of the column, the lateral deflection of the column at mid-height and the rotation of the end plates of the column were measured with varying frequencies, depending on the rate of change of the measured quantities.

The column was considered to have failed, and the test was terminated, when the axial hydraulic jack, which has a maximum speed of 76 mm/min, could no longer maintain the load.

6. TEST RESULTS

This section contains results and observations for the test. The basic characteristics, already given in Table 1, are reiterated.

Date tested:	June 12,1991
Loading:	1400 kN, Concentric

Specimen Characteristics:

Cross section:	300 × 300 mm
Length:	3810 mm
Reinforcement	4 ϕ 16 mm, A500 HW, ribbed bars
Casting day:	January 25, 1991

Elevation, cross section and finishing detail:	Fig. 1
Layout of thermocouples:	Figs. 2 and 3

Measured Properties:

Concrete Strength

150 mm cube strengths:	29.6 MPa at 7 days 37.5 MPa at 28 days 37.8 MPa at test date
100 mm drilled cylinder strength:	40.3 MPa on October 18, 1991

Steel Strength

Yield and ultimate strength of the reinforcing bars: see Table 2.

Moisture Condition

Relative humidity in long test column measured with Vaisala moisture sensor:	99 % R.H. at test date

Results:

Test duration:	60 min
Type of failure:	Compression
Temperatures:	Tables 4-6
Axial deformation:	Table 7
Horizontal deformation at midspan:	Not obtained due to early spalling of the concrete, causing the measurement markings to come off.

Observations:

At 10 Min:
- The concrete spalled at several locations, mainly at the North and West side at about 1/3 of the column height (the door of the furnace is at the East side) and at at the south side at about 3/4 height.
- Ties were visible at the locations of the spalling. In the lower section a

reinforcing bar was visible at the North-West corner.
- Moisture was visible at the West side surface.
- Because the measurement markings for lateral midheight deflection on the column came off with the spalled concrete, these measurements were no longer possible.

at 50 min:
- Cracks were visible at the North-West corner at approximately midheight, at the North-East corner at approximately 1/3 height and at the South-East corner at approximately 2/3 height. All cracks were close to the locations where the concrete spalled.

at 60 min:
- The column failed due to crushing of the concrete and buckling of the reinforcing steel at the locations where the concrete spalled (Figs. 7-10).

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TABLE 1

Concrete column details

Cross Section:	300 × 300 mm
Length:	3810 mm
Reinforcement:	4 ϕ 16 mm, A500 HW, ribbed bars
Casting Date:	January 25, 1991
Test Date:	June 12, 1991
Moisture Condition of Specimen:	99 % R.H. at test date
Concrete Strength:	
150 mm Cube:	29.6 MPa at 7 days
	37.5 MPa at 28 days
	37.8 MPa at test date
100 mm Drilled Cylinder Strength:	40.3 MPa on October 18, 1991

TABLE 2

Average tensile strength of reinforcing bars

(three tests for each bar size, steel grade A 500 HW)

Bar Size (mm)	Yield strength (MPa)	Ultimate strength (MPa)
6.0	510.0	696.3
12.0	543.7	679.7
16.0	582.3	657.3

TABLE 3

Batch quantities and properties of concrete

Component	Quantity (kg/m^3)
Cement	371.9
Fine aggregate:	
0 - 0.6 mm	400.0
0.5 - 1.2 mm	217.2
1 - 2 mm	331.3
Coarse aggregate:	
2 - 3 mm	170.3
3 - 5 mm	118.8
5 - 10 mm	559.4
Water	200.0
Super plasticizer:	
SP 62	1.86
Water cement ratio	0.54

Average 150 mm cube strength in MPa:

at 7 days	29.7
at 28 days	37.5

TABLE 4. Cross-section temperatures measured at level I

Time (min)	Furnace temp. (°C)	Temperature (°C) measured at location of thermocouple No.															
		1	2	3	4	5	6	7	8	9	10	11	12	13	15	16	17
0	69	29	31	29	30	31	32	24	24	24	24	25	25	24	24	24	24
2	408	58	89	79	78	84	102	25	25	25	26	28	30	24	24	24	24
4	638	117	166	140	153	175	194	31	30	31	33	48	60	24	24	24	24
6	648	157	214	187	202	169	247	53	44	49	56	78	104	24	24	24	24
8	672	188	251	225	242	100	275	86	71	75	85	103	118	24	24	24	24
10	704	224	289	267	287	100	299	99	98	103	114	114	122	25	26	24	24
12	725	258	323	308	329	103	327	108	137	129	134	121	135	28	27	27	27
14	736	291	349	341	363	205	369	109	132	129	130	139	155	31	29	28	29
16	764	322	376	372	395	282	418	110	125	125	127	157	178	39	33	28	24
18	798	359	418	410	438	343	474	117	120	129	140	176	199	50	38	30	24
20	809	393	455	442	471	388	514	142	129	145	158	197	216	59	43	32	25
22	826	425	490	471	500	428	549	163	143	163	176	217	232	71	47	34	26
24	837	453	521	495	524	457	578	184	157	181	198	239	249	78	51	37	27
26	571	478	548	517	546	487	605	204	172	199	221	259	265	81	55	40	28
28	860	500	571	535	564	511	627	224	188	218	243	279	281	83	58	42	30
30	874	521	593	554	584	535	650	243	204	237	264	297	296	85	62	45	31
32	879	539	611	570	601	555	668	262	221	257	282	314	311	88	65	48	34
34	891	557	630	587	619	577	688	280	237	278	298	329	323	89	67	51	36
36	604	571	645	600	634	595	703	298	253	297	313	344	336	89	70	54	38
38	908	587	661	615	649	614	721	315	269	317	326	358	345	90	75	57	41
40	911	600	675	628	661	631	736	331	284	335	339	371	356	91	79	60	43
42	924	613	689	641	674	649	752	348	298	353	352	383	365	93	84	63	46
44	931	626	702	653	686	666	766	363	311	371	366	395	374	97	88	66	49
46	933	637	712	663	695	681	777	378	324	389	381	406	384	98	92	69	51
48	942	648	724	674	707	696	791	393	337	407	396	417	393	101	98	73	54
50	940	658	735	685	718	710	802	407	349	425	410	427	400	103	103	76	56
52	950	669	747	696	729	726	816	420	361	440	425	437	409	105	109	80	59
54	956	680	758	707	739	742	826	434	372	456	440	446	416	108	112	83	62
56	963	690	769	717	748	758	836	447	384	469	454	455	424	109	115	87	65
58	973	700	780	727	758	773	845	460	395	482	468	465	431	111	121	90	67

TABLE 5. Cross-section temperatures measured at level II

Time (min)	Furnace temp. (°C)	Temperature (°C) measured at location of thermocouple No.					
		18	19	20	21	22	23
0	69	27	29	24	24	25	26
2	408	46	70	25	25	28	36
4	638	109	139	31	30	47	80
6	648	141	187	56	48	79	121
8	672	176	224	91	77	107	132
10	704	206	257	108	111	126	158
12	725	238	293	112	133	130	182
14	736	266	304	111	137	131	212
16	764	297	166	115	136	135	169
18	798	331	292	128	140	140	169
20	809	359	366	147	157	157	233
22	826	389	418	169	175	197	277
24	837	417	457	192	193	227	312
26	571	443	490	214	211	252	341
28	860	466	515	235	229	275	367
30	874	487	538	255	247	295	389
32	879	506	557	274	265	313	408
34	891	524	576	293	283	331	425
36	604	539	593	311	299	347	440
38	908	554	609	329	315	361	454
40	911	569	621	346	330	375	467
42	924	582	632	362	345	388	479
44	931	595	645	377	361	400	491
46	933	607	655	392	376	413	502
48	942	619	668	407	391	424	513
50	940	630	680	421	406	435	525
52	950	641	693	434	421	446	536
54	956	-	715	447	436	456	547
56	963	-	716	460	449	466	557
58	973	-	727	471	459	477	567

TABLE 6. Cross-section temperatures measured at level III

Time (min)	Furnace temp. (°C)	Temperature (°C) measured at location of thermocouple No.								
		24	25	26	27	28	29	30	31	32
0	69	32	30	25	25	25	25	28	28	24
2	408	74	62	27	26	26	26	37	38	24
4	638	137	116	35	32	33	33	76	79	24
6	648	179	154	56	49	51	52	111	109	24
8	672	215	189	83	75	82	79	127	124	24
10	704	255	223	114	103	113	105	152	151	24
12	725	290	251	145	108	122	130	173	170	23
14	736	328	281	149	123	174	151	202	196	22
16	764	363	304	151	136	241	145	225	209	24
18	798	398	327	166	200	269	150	237	228	24
20	809	421	350	189	254	332	175	262	250	25
22	826	453	374	215	303	379	198	297	271	26
24	837	483	406	241	346	408	220	327	302	27
26	571	512	438	266	384	436	241	353	331	28
28	860	536	465	290	413	465	261	377	358	30
30	874	558	491	313	431	499	280	398	382	32
32	879	578	513	334	441	534	299	418	404	34
34	891	598	534	354	453	565	317	437	425	36
36	604	614	552	372	466	591	333	454	443	38
38	908	631	570	390	483	615	349	470	460	41
40	911	646	586	407	499	636	365	486	477	43
42	924	660	601	423	517	653	380	500	491	46
44	931	673	615	438	532	-	394	514	505	49
46	933	684	627	452	541	-	409	527	518	52
48	942	696	640	466	550	-	424	539	530	55
50	940	706	651	479	561	-	438	550	542	58
52	950	717	662	492	568	-	452	561	553	61
54	956	728	674	504	577	-	466	572	564	64
56	963	739	684	515	586	-	480	584	574	67
58	973	750	694	527	595	-	493	596	584	70

TABLE 7. Axial deformation of column

Time (min)	Axial deformation (mm)
0	0.00
2	0.00
4	0.00
6	0.00
8	0.03
10	0.10
12	0.18
14	0.18
16	0.18
18	0.18
20	0.18
22	0.19
24	0.19
26	0.19
28	0.13
30	0.01
32	-0.14
34	-0.31
36	-0.51
38	-0.71
40	-0.93
42	-1.17
44	-1.43
46	-1.72
48	-2.04
50	-2.38
52	-2.77
54	-3.21
56	-3.72
58	-4.32

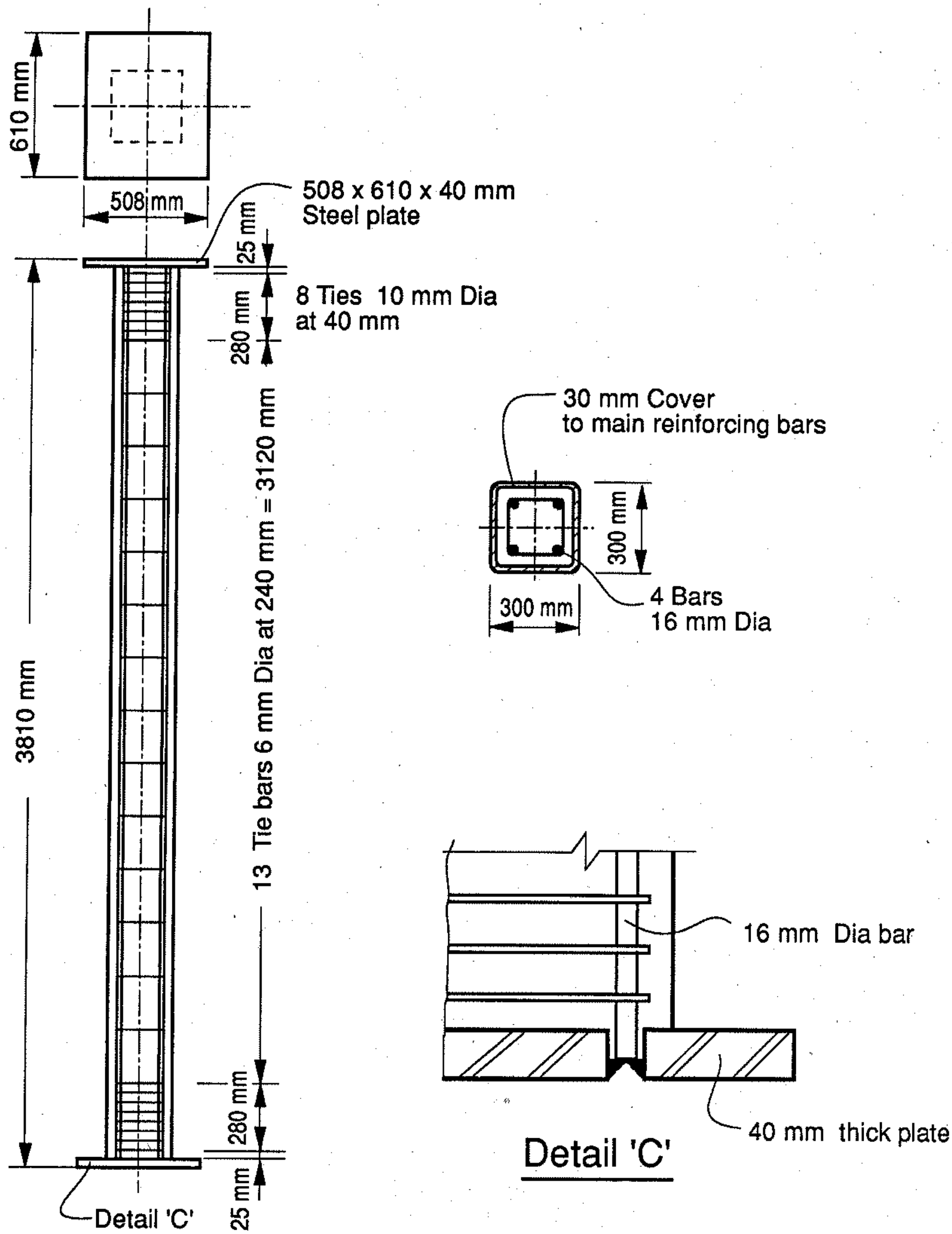


Figure 1

Elevation, cross section and finishing detail of the reinforced concrete column

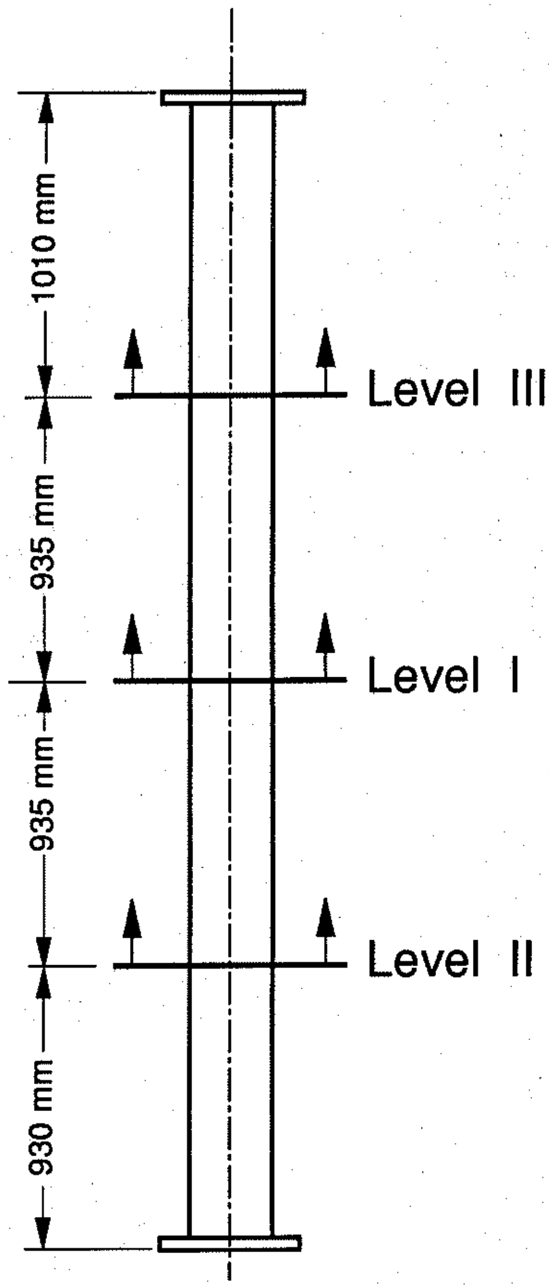
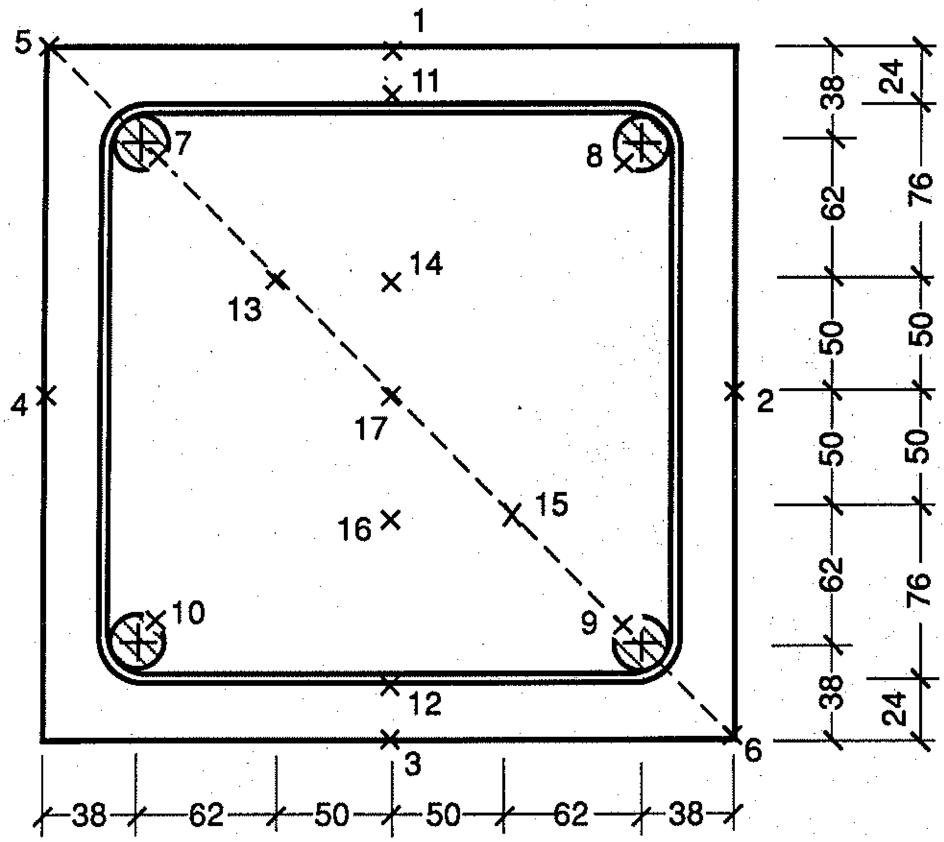


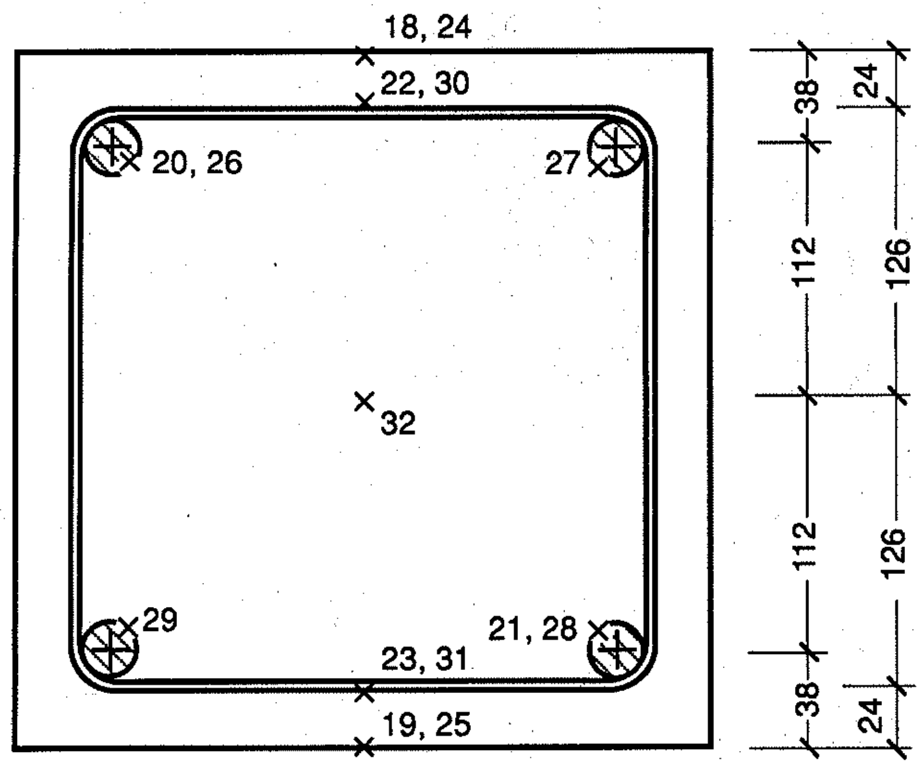
Figure 2

Levels at which thermocouples in the concrete column were installed

BR 7151-2



Level I



Levels II and III

Thermocouples Nos. 18 - 23 at level II

Thermocouples Nos. 24 - 32 at level III

Figure 3

Location of thermocouples at various levels in column

BR 7151-3

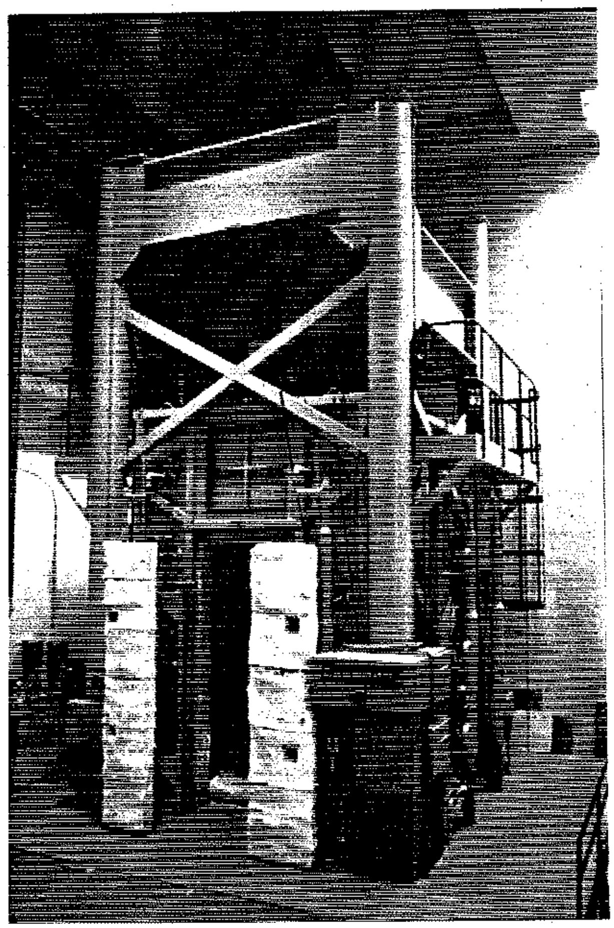


Figure 4

Test Furnace

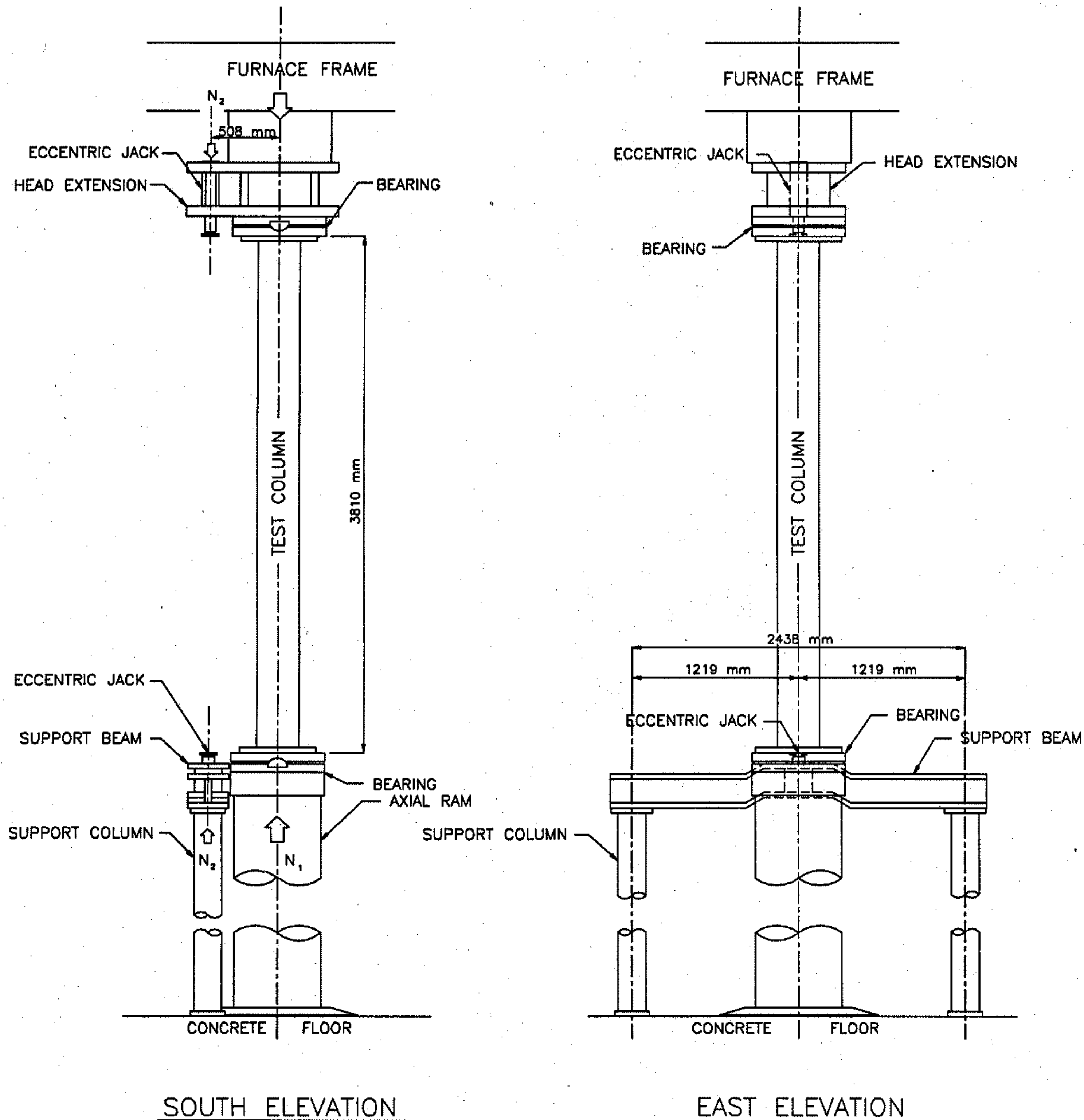


Figure 5

Loading device of column test facility

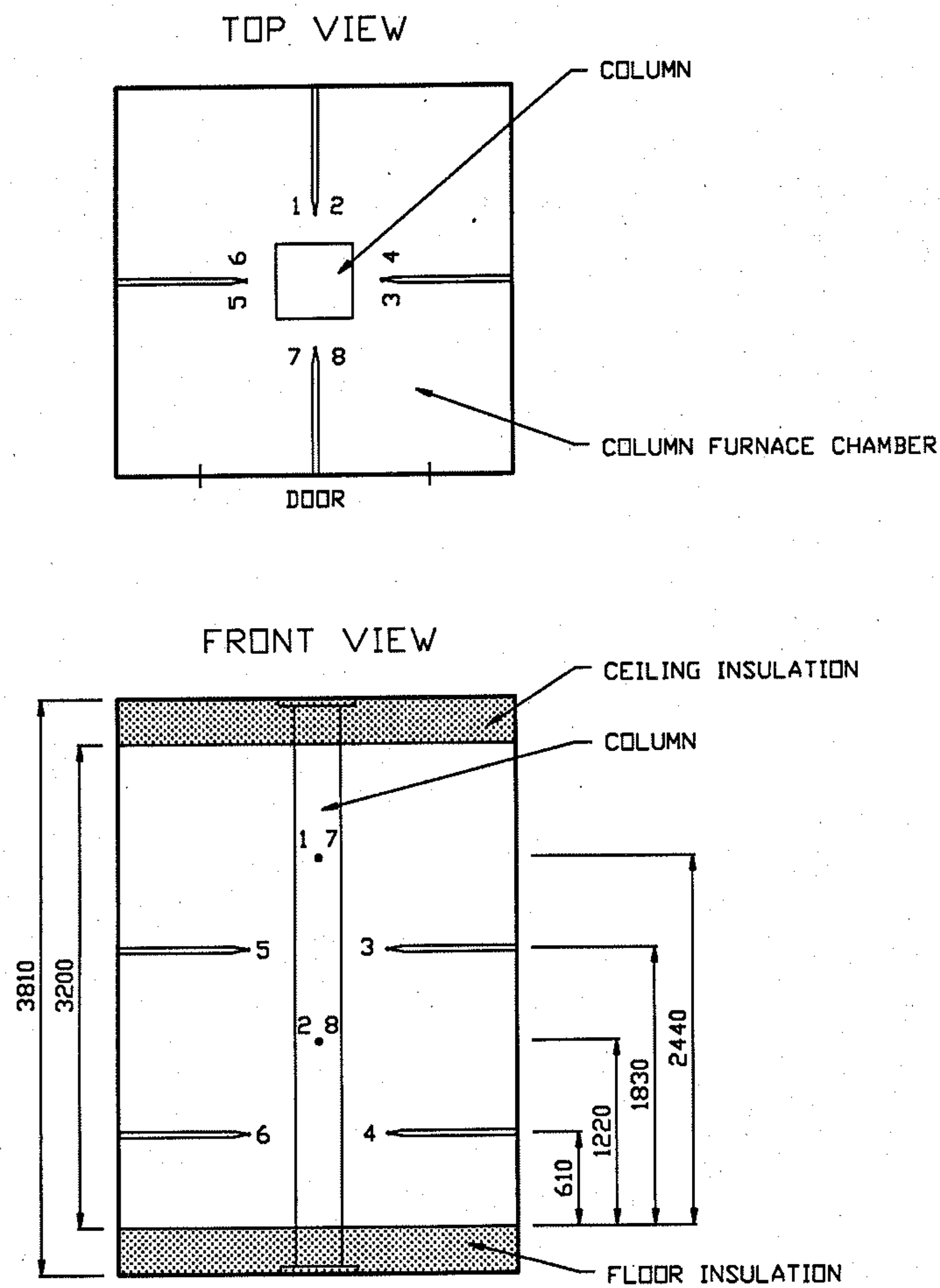


Figure 6

Location and numbers of thermocouples in column furnace chamber

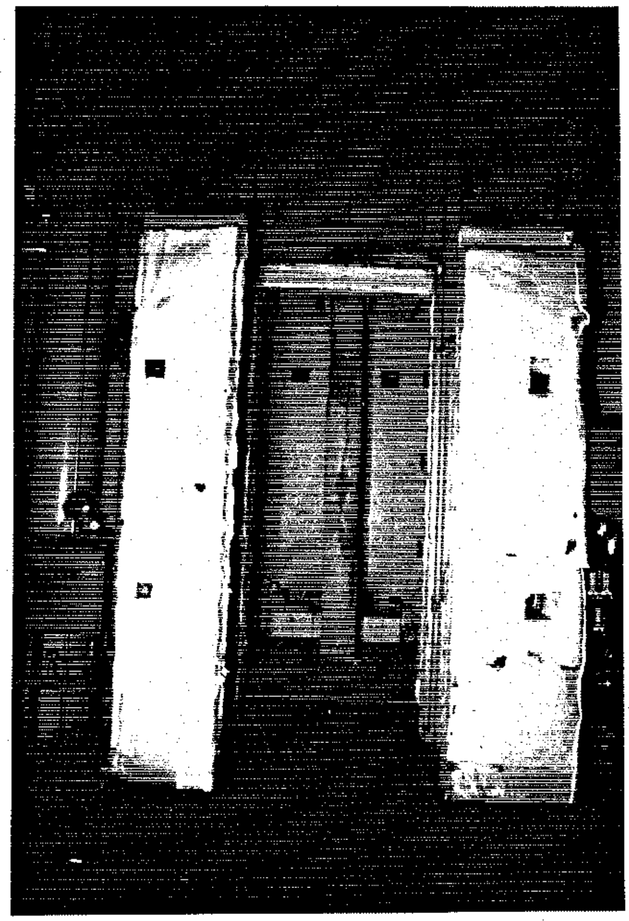


Figure 7

East side of column after test

Figure 8

West side of column after test

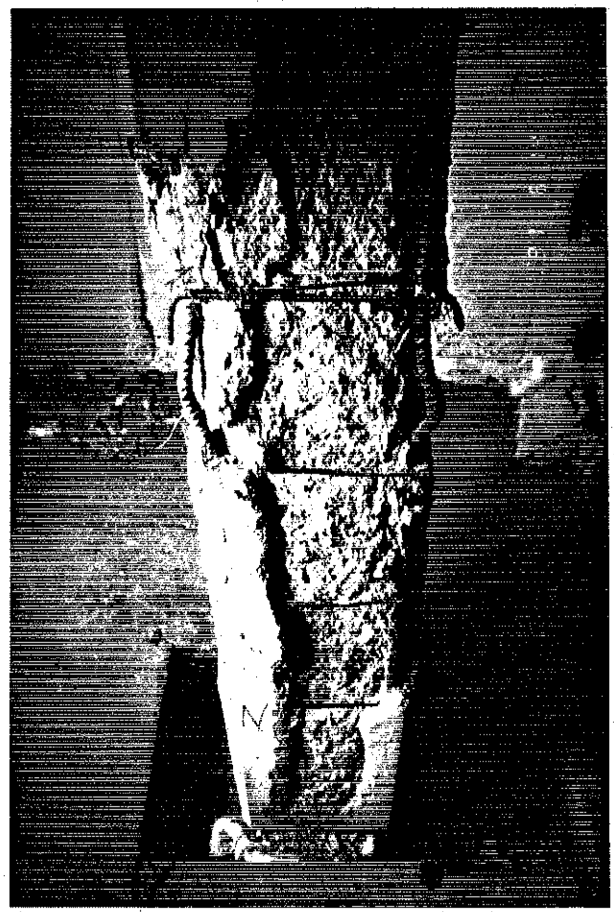


Figure 9

North side of column after test

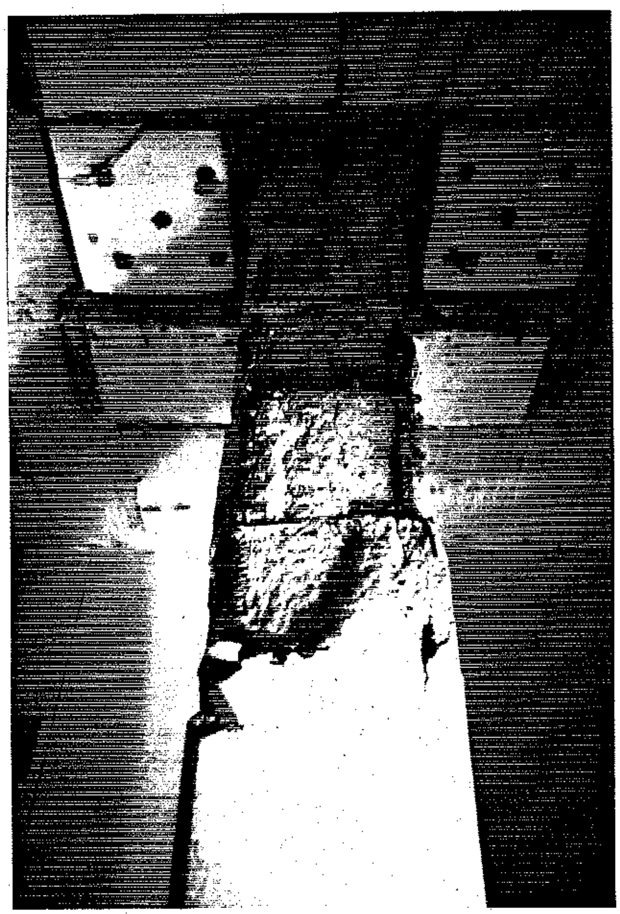


Figure 10

South side of column after test

APPENDIX

Methods and Instruments

The following methods and instruments were used to measure the thermal properties of the concrete of the VTT column:

Mass Loss

The mass loss curve was produced by a DuPont 951 Thermogravimetric Analyzer. The specimens that were tested weighed between 30 and 40 mg. Scanning rates of 10°C/min in a nitrogen atmosphere and of 20°C/min in air static were used.

Thermal Expansion

The thermal expansion curve was produced by a Theta Dilatronic apparatus. The specimens were 40 mm long and 12.5 mm square in cross-section. The rate of heating was 10°C/min in air static from room temperature to 1200°C.

Specific Heat

The specific heat of the concrete was measured with two instruments: A DuPont 2910 Differential Scanning Calorimeter (DSC) and a DuPont 1600°C High Temperature Differential Thermal Analyzer (DTA).

The specimens tested in the DSC weighed between 30 and 40 mg. The DSC analyzed the samples from room temperature to 725°C in a nitrogen atmosphere. A scanning rate of 10°C/min was used. The error in reproducibility of the specific heat, determined with Aluminum, was 1.5%.

The DTA was used to determine the specific heat of the concrete from 725°C to 1000°C. Scanning rates of 10°C/min and 20°C/min were used on 50 mg samples in both a nitrogen atmosphere and in air static. The DTA error in reproducibility was for silver wire 3%.

Thermal Conductivity

A TC-31 Thermal Conductivity Meter made by Kyoto Electronics was used to determine the thermal conductivity curve.

TABLE A1. MASS LOSS OF CONCRETE OF VTT COLUMN AS A FUNCTION OF TEMPERATURE

Temperature (°C)	Mass Loss (%)
50	99.88
100	98.93
150	97.97
200	97.51
250	97.27
300	97.06
350	96.88
400	96.68
450	96.52
500	96.09
550	95.97
600	95.7
650	95.26
700	94.46
750	93.97
800	93.88
850	93.77
900	93.68
950	93.6
1000	93.55

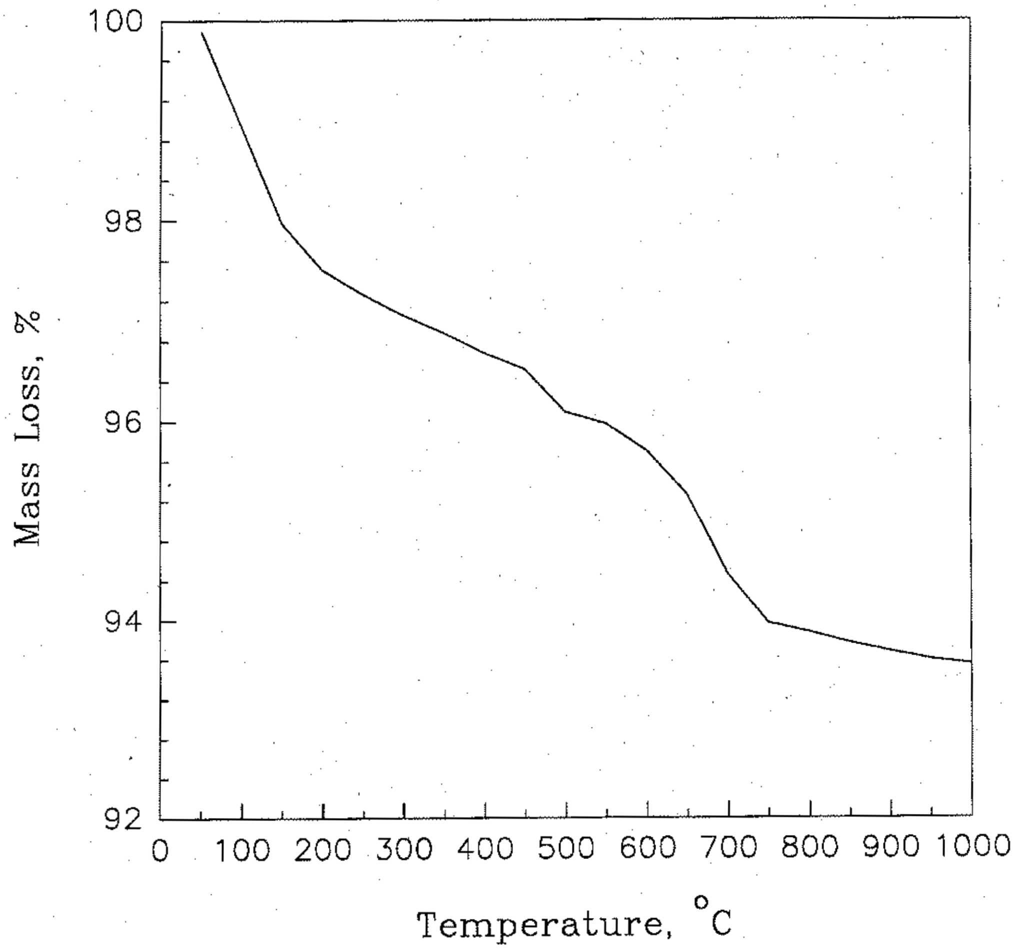


Figure A1

Mass Loss of Concrete of VTT Column as a Function of Temperature

TABLE A2. THERMAL EXPANSION OF CONCRETE OF VTT COLUMN AS A FUNCTION OF TEMPERATURE

Temperature (° C)	Expansion	Temperature (° C)	Expansion	Temperature (° C)	Expansion	Temperature (° C)	Expansion
19.2	0.0%	297.0	0.22%	556.8	0.62%	825.6	1.50%
30.0	0.01%	308.2	0.24%	566.0	0.66%	834.0	1.50%
44.2	0.02%	322.9	0.25%	578.8	0.78%	844.8	1.51%
52.3	0.02%	333.6	0.27%	588.4	0.88%	855.6	1.52%
64.6	0.03%	340.8	0.28%	597.6	0.92%	866.0	1.53%
77.4	0.04%	354.8	0.29%	610.0	0.95%	877.2	1.54%
85.9	0.05%	365.6	0.31%	619.2	0.97%	885.2	1.55%
98.6	0.06%	375.6	0.32%	631.6	0.98%	890.4	1.55%
107.2	0.07%	389.2	0.33%	640.4	0.99%	906.4	1.56%
119.3	0.09%	399.6	0.35%	649.6	1.01%	922.8	1.56%
131.0	0.10%	413.2	0.36%	662.0	1.04%	938.8	1.56%
138.8	0.10%	422.8	0.37%	671.2	1.07%	957.6	1.56%
150.9	0.11%	430.0	0.39%	680.0	1.11%	968.4	1.55%
163.9	0.11%	440.4	0.40%	692.0	1.20%	976.4	1.54%
172.8	0.12%	450.0	0.41%	701.2	1.28%	986.8	1.52%
182.0	0.12%	459.6	0.42%	710.0	1.36%	999.6	1.51%
190.8	0.13%	469.6	0.44%	722.0	1.43%	1010.0	1.48%
204.0	0.14%	479.6	0.45%	730.4	1.45%	1020.4	1.45%
221.2	0.15%	489.6	0.46%	736.8	1.46%	1030.8	1.41%
233.9	0.16%	499.6	0.48%	748.0	1.47%	1035.2	1.39%
242.2	0.17%	509.2	0.50%	759.6	1.47%		
254.3	0.18%	518.8	0.52%	776.8	1.48%		
266.2	0.19%	528.8	0.54%	790.4	1.48%		
277.8	0.21%	538.0	0.56%	803.6	1.48%		
289.2	0.22%	547.6	0.59%	812.0	1.49%		

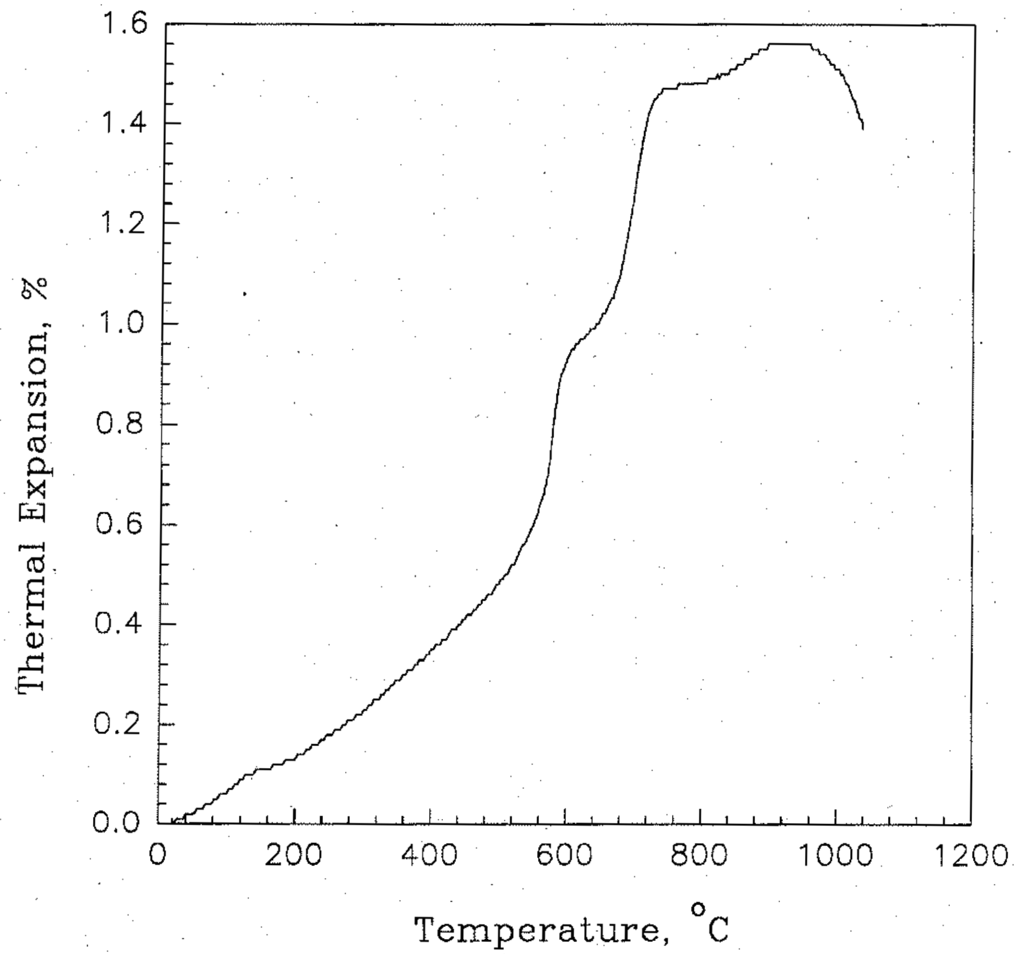


Figure A2

Thermal Expansion of Concrete of VTT Column as a Function of Temperature

TABLE A3. SPECIFIC HEAT OF CONCRETE OF VTT COLUMN AS A FUNCTION OF TEMPERATURE

Temperature (°C)	Specific Heat (J/kg°C)
32	927
74	1612
116	1252
180	971
200	971
390	942
420	1646
442	900
474	883
490	897
560	1169
574	1482
576	1250
594	1161
658	1398
674	1543
720	705
1000	725

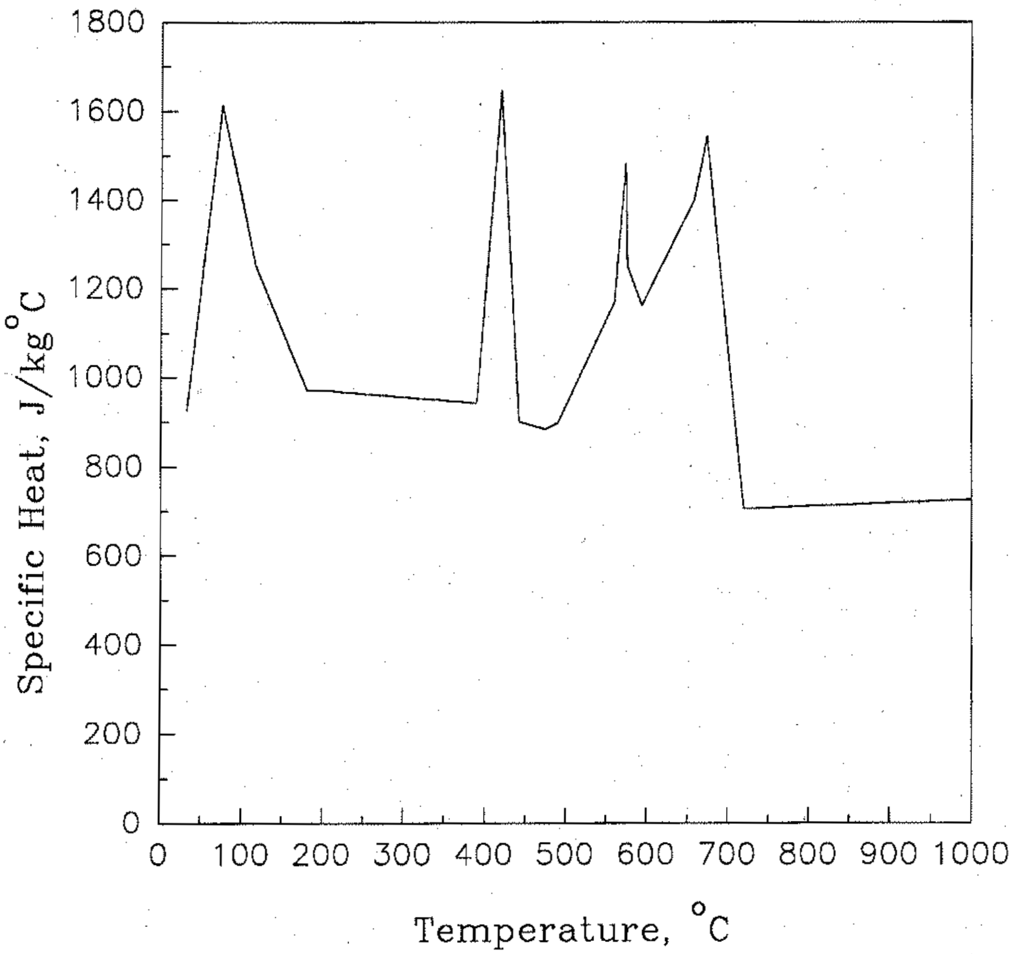


Figure A3

Specific Heat of Concrete of VTT Column as a Function of Temperature

TABLE A4. THERMAL CONDUCTIVITY OF CONCRETE OF VTT COLUMN AS A FUNCTION OF TEMPERATURE

Temperature (°C)	Thermal Conductivity (W/mK)
24	1.773
75	1.678
75	1.647
100	1.536
100	1.535
194	1.418
194	1.421
289	1.252
289	1.255
387	1.133
387	1.135
490	1.029
490	1.029
594	0.998
594	0.999
698	0.958
698	0.958
800	0.959
800	0.958
900	0.939
900	0.940
1000	0.923
1000	0.923

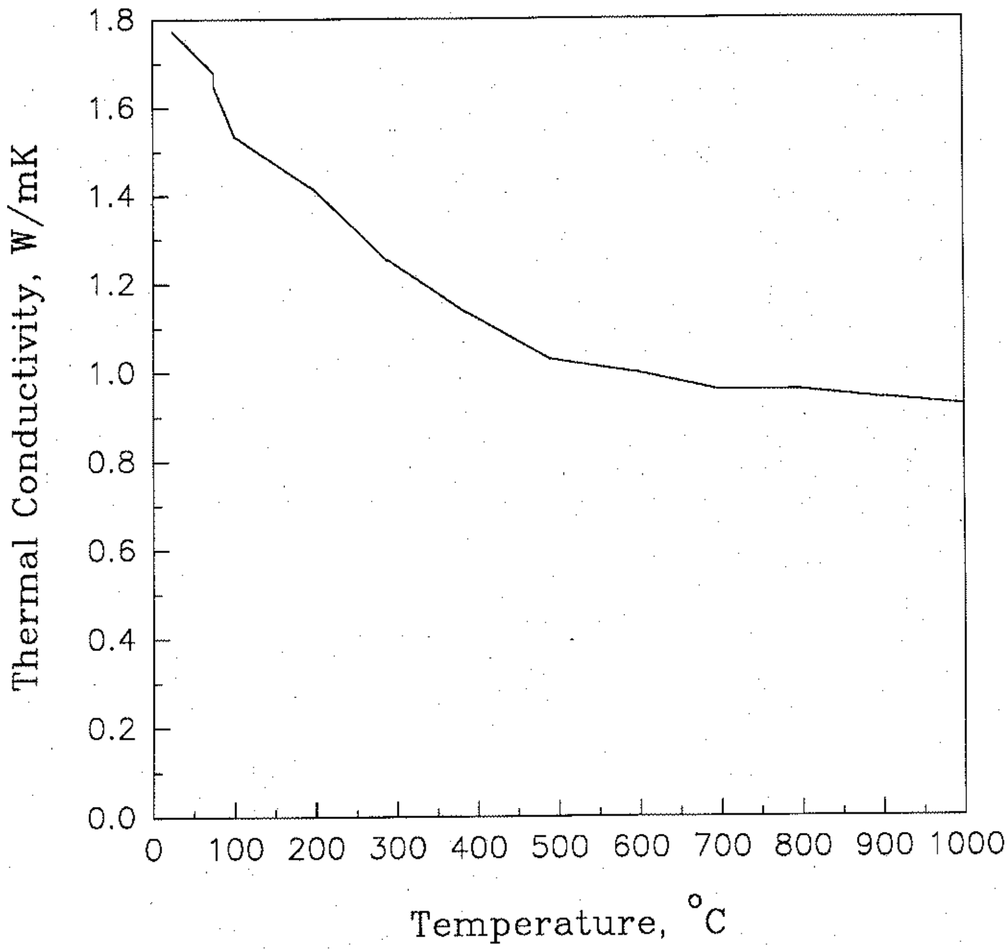


Figure A4

Thermal Conductivity of Concrete of VTT Column as a Function of Temperature