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Innovative self-compacting concrete – Development of test methodology for determination of fire spalling

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Abstract

Different qualities of self-compacting and tunnel concretes have been fire tested with the objective to develop a test methodology for determination of the risk and amount of spalling when exposed to fire. A total of ten different concretes were included in the study. The compressive strength of the concretes ranged from 30 MPa up to 100 MPa. The main objective with the study was to develop a test methodology including both a full scale reference test as well as a small scale test with which the risk and amount of spalling can be determined.

In order to ensure that some concretes would spall during the fire tests it was decided to use a relatively high moisture content, i.e. the concrete was tested at a young age. The tunnel concretes had also been cured under water until time of testing. Hence the amount of spalling were in some cases much more than expected in practice.

Severe spalling was observed in many concretes, both in the full scale and the small scale test specimens. In some concretes were fibres of polypropylene included and these concretes showed a very good behaviour with respect to risk for spalling.

The results from the present study show that it is possible my means of small scale tests get the same results regarding risk and amount of spalling as in the full scale reference scenario. Although, it is of great importance that the small scale specimens are loaded similarly as the reference specimens. It is also important the boundary conditions are similar, i.e. the thickness shall be the same and the width and length shall be large enough. In the present study small specimens with the dimensions 600 x 500 x 200 mm^3 were used and the amount of spalling obtained was similar to that of the reference specimens.

Also small cylinders were tested. These specimens gave generally a lower amount of spalling and it was not possible to compare the depth of the spalling with the reference specimens due to the different geometries. The cylindrical specimens are also more difficult to use since it is difficult to apply load without affecting the boundary conditions.

Key words: Self-compacting concrete, tunnel concrete, fire resistance, spalling, testing

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Preface

This work was initiated and finanicial supported by the Development Fund of the Swedish Construction Industry (SBUF), Skanska Asfalt och Betong, Skanska Prefab AB, Banverket (the Swedish Rail Administration), Vägverket (the Swedish Road Administration) and Cementa AB who are gratefully acknowledged. The work presented in this report has mainly been performed by SP Swedish National Testing and Research Institute who also has contributed financially to the project. Skanska Asfalt och Betong as well as Skanska Prefab have developed the self-compacting concrete recipes and performed the manufacturing of the specimens of self-compacting concrete. Banverket has contributed with the concrete recipes for the tunnel concretes.

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Summary

Several different qualities of concrete including both self-compacting and tunnel concretes have been fire tested. The objective of the study was to develop a test methodology for determination of the probability and the amount of spalling of concrete when exposed to fire. The methodology should include a reference scenario as well as a small scale test method.

An extensive test program has been carried out where ten different concretes have been tested. For each concrete has several different test specimens been manufactured with different geometries in order to find a suitable small scale test giving comparable results with the reference scenario. The reference specimens are quite large, 1800 x 1200 mm^2, and with a thickness similar to that used in practice. Hence the reference specimens must be tested on a large horizontal furnace and the tests are therefore costly. A more cost effective small scale test is needed when many different qualities of concrete and other factors shall be studied.

Within the present project different small scale specimens such as cylinders, small slabs and columns were studied and compared with the results from the large reference specimens. Some of the small scale specimens were tested both in loaded and unloaded conditions. Only compressive loading was applied on the small specimens. Although, most of the small specimens were tested unloaded since it is much simpler, and thus not as costly.

Since the objective was to find a method for determination of spalling, it was decided that most of the specimens tested should show spalling to some extent. Therefore the tests were carried out on relative young specimens, or specimens cured in water, in order to have a high moisture content. Thus cannot the results fully be applied to practice since the concrete in many constructions have a lower moisture content and thus a lower risk for spalling.

The main result from the study was that it is possible to get approximately the same results with respect to probability and amount of spalling by using a small scale specimen as for the reference specimens. For concrete with a thickness of 200 mm it is shown that a small slab with the dimensions 600 x 500 x 200 mm^3, loaded in compression during the fire test, gives approximately the same amount of spalling as the full scale specimens. Unloaded small slabs gave also some spalling but to a much lower degree.

Also loaded and unloaded cylinders with a diameter of 150 mm and length of 450 mm were examined. The load was applied by a bar going through a pipe in the centre of the cylinder. Generally the spalling of the cylinders was less than that of both the small and the large slabs. Reasons for this may be that water could escape from the specimen around a centrally placed pipe and that it was not possible to ensure that the compressive loading was kept during the whole test. If the loading bar is heated during the test the load decreases.

1 Introduction

1.1 Background

Despite the long tradition of using concrete, knowledge on performance of concrete structures when exposed to fire is still not satisfactory. There are several problems which are still not sufficiently recognized and investigated.

Reinforced structural concrete exposed to fire may be damaged because of:

- decrease of strength and stiffness of reinforcement bars when obtaining temperatures above 400-500^{o}C
- decrease of strength and stiffness of concrete when obtaining temperatures above 400-500^{o}C
- explosive spalling
- loss of bonding between concrete and reinforcement
- damage of joints and connections due to thermal elongation and thermal gradients, and large deflections of concrete elements
- loss of separating function caused by improper location and size of gaps and dilatation joints

There are, as shown above, several ways concrete may be damaged when exposed to fire. In the following only spalling will be considered. A difference between conventional vibrated concrete and self-compacting concrete is the use of a fine filler. The filler could be glass or limestone powder. By adding filler, the concrete will be denser which could lead to a lower permeability. Earlier studies made on high performance concrete as well as self-compacting concrete, showed that spalling occurred to a considerably higher degree than for conventional concrete, see Oredsson (1997) and Boström (2002).

There are today no standardized methods for the determination of spalling and its effect on the structural behaviour of the concrete element/structure. When tests presently are carried out the responsible fire laboratory, or the client, defines how to test the concrete. Since tests of full scale specimens generally are very expensive, small specimens are often chosen in order to keep the costs down. When comparing results on spalling of self-compacting concrete made at different laboratories the results are contradictory in the sense that some resulted in extensive spalling while other almost no spalling at all, see for example Boström (2002) and CERIB (2001). It is likely that the geometry of the test specimen and the load level and configuration have a great effect on the spalling. This assumption is based on the available test results where loaded medium and full scale tests have resulted in severe spalling while unloaded small scale tests have not spalled more than conventional concrete.

In the present European standards on fire resistance, very little is said about spalling. It is only in the general test standard EN 1363-1 that spalling is mentioned, and here very vaguely. Quoting the standard it says:

"Observations shall be made of the general behaviour of the test specimen during the course of the test and notes concerning phenomena such as smoke emission, cracking, melting, softening, spalling or charring etc. of materials of the test specimen shall be made."

Thus only the spalling that takes place during the test shall be observed and noted. The standard does not say anything about measurements of the amount of spalling, only that it shall be observed. In all other fire resistance standards that can be used on concrete, i.e. the EN 1365 series on load bearing structures and ENV 13381-3 on protection of concrete members, only reference to measurements in accordance with EN 1363-1 is given. It is therefore of great importance that a methodology is developed with which the spalling behaviour of all types of concrete can be determined.

Self-compacting concrete has been met with great attention. As an example a project on self-compacting concrete has been nominated as one of the finalists to the European Descartes prize for 2002. Self-compacting concrete is gaining more of the market, and is now widely used for different constructions. It is therefore of great importance that guidance on how to produce self-compacting concrete with good fire spalling properties is worked out and presented to industry and other stakeholders.

1.2 Objective

This report covers one part of a larger project divided into four work packages (WP). The objectives of the full project are the following;

1. To prepare a methodology for determining the risk and amount of spalling of concrete. This includes:
   - comparative study of different test methods and test results
   - development of a small scale or intermediate scale test procedure
   - verification of the developed test procedure
2. To determine experimentally the effect of different factors, such as moisture content, geometry etc, on the fire spalling.
3. To develop a guidance on how to produce fire spalling resistant self-compacting concrete.

This report covers WP 1 which has as objective to develop a methodology for determination of spalling of concrete. A small scale test as well as a reference scenario shall be developed. The work has been divided into two parts, of which this report covers the second part. The first part of the project has been reported in a project report from SP Fire Technology, BRk 6036. This report will also include a summary of the first part as well as conclusions covering both parts.

In the first part of the WP three different concrete types were tested. One conventional concrete, one with 6 % silica, and one with limestone filler. These concretes were manufactured with and without addition of polypropylene fibers. All concretes had a w/c of 0.38. The concretes were not designed as self-compacting but were typical concretes to be used in tunnels. Different types of test specimens were manufactured using the same concrete, ranging from small scale specimens up to full scale specimens which are considered to be references. The fire exposure was the same for all large specimens and some of the small specimens, and a specially designed fire curve will be used which is calculated to simulate the actual fire load in the City tunnel to be built in Malmö.

Table 1. Test program for the first phase of WP1.

Type	Geometry	Fire exposure
Reference	1800x1200x400 mm	One-sided fire exposure
Qube	150x150x150 mm	Five-sided fire exposure
Plate	500x500x100 mm	Five-sided fire exposure and one-sided exposure with the standard time-temperature-curve
Cylindrical	Ø = 150 mm, l = 300 mm	Fire exposure around the cylinder (not on the end surfaces) and special test made at DTU
Cylindrical	Ø = 150 mm, l = 450 mm	Fire exposure around the cylinder (not on the end surfaces)
Column	200x200x1000 mm	Fire exposure around the box (not on the end surfaces)

The second part of the WP, i.e. the work presented here, has focused on the effects of loading conditions and eventual possibilities to use a small scale furnace to determine spalling. It is well known that the loading conditions affect the fire spalling. Concrete is used for its good mechanical characteristics in compression as well as a protection of the reinforcement. Hence concrete structures are generally loaded in compression but may as well be loaded in tension and bending. In a fire scenario the fire exposed face/faces of the concrete structure can thus be loaded in different ways. An hypothesis is that concrete loaded in tension show better fire spalling characteristics due to tensile cracking which may increase the permeability and hence improve the vapor transport.

Table 2. Test program for the second phase of WP1.

Type of specimen	**Loading**	**Fire curve**
Slab 1800x1200x200 mm	Pre-stressed in compression to 30 % of f_u	EN 1363-1
Beam 3600x600x200 mm	Bending with tension on fire exposed face 30 % of f_u.	EN 1363-1
Plates 500x600x200 mm	Unloaded and loaded in compression	EN 1363-1
Cylinders ∅=150 mm, l=450 mm	Unloaded and loaded in compression	EN 1363-1

1.3 Limitations

This report covers a part of the project and is focused on comparisons between different small scale test specimens and large scale specimens. Only four different recipes of self-compacting concretes are included of which one includes fibres of polypropylene.

The self-compacting concretes were cured in air for three months. The moisture conditions in the fire tested specimens were not measured. Instead the moisture content was measured on cubes casted at the same time and with the same concrete as that of the test specimens. The tunnel concretes were cured under water for three months. Also here the moisture content was measured on separate cubes. Hence the moisture content, and the moisture profile within the fire tested specimens is not known.

2 Materials and specimens

2.1 Concrete recipes and manufacturing

2.1.1 Self-compacting concrete

Four different concrete recipes were developed. Initially self-compacting concretes with water-powder ratio w/p = 0.40 and w/p = 0.60 with and without fibres of polypropylene. It was not possible, within the frame of the present project, to find recipes for w/p = 0.60 that could be defined as self-compacting concrete without other problems such as separation. Hence it was decided to find recipes with w/p = 0.31 without fibres, w/p = 0.40 with and without fibres, and w/p = 0.55 without fibres. The recipes were developed by Skanska Asfalt och Betong and the final recipes are shown in table 3.

Table 3. Concrete recipes.

Recipe code		**w/p 0.30**	**w/p 0.40**	**w/p 0.40 fib**	**w/p 0.55**
Dry materials (kg/m^3)					
Cement	Slite (CEM I)	439.32	381.57	380.76	301.51
Limestone filler	Limus 25	126.38	118.68	119.24	77.39
Fine gravel	0-8 Sätertorp	1027.33	1016.95	899.96	941.66
Coarse gravel	8-16 Sätertorp	591.65	602.69	721.90	754.52
Plasticizer*	CemFlux Prefab	8.76	5.24	5.73	0
Plasticizer*	CemFlux PrefabS	0	0	0	3.26
Plasticizer	(% of C+F)	1.55%	1.05%	1.15%	0.86%
Fibres	Fibrin 18μm	0	0	1.0	0
Water/moisture (kg/m^3)					
Water		122.37	141.21	149.69	163.82
Dilution water		10.03	10.01	10.02	9.05
Moisture in material		43.00	46.34	37.54	37.08
w/c-ratio		0.399	0.518	0.518	0.696
w/p-ratio		0.310	0.395	0.395	0.554
Slump flow	mm	750	700	640	630
Slump flow 500 mm	s	4	3	4	2

* Plasticizers are given as weight in diluted form, as delivered. The moisture is included in ”Moisture in material” in the table.

The manufacturing of the test specimens was performed at Skanska Prefab in Strägnäs, Sweden, during September 25-26, 2003. The only change to the recipes during the manufacturing was the amount of plasticizer. The values given in table 3 are the ones used for the final manufacturing. The air content was estimated to 2 % in all recipes.

A total of 12 cubes were made from each recipe. 6 of these cubes were used for determination of strength for unstressing, 7 days and 28 days strength. These cubes were water cured and tested in accordance with SS 13 72 10. Three of the remaining cubes were used for measurement of compressive strength and moisture content at the time of testing. These cubes were stored in the laboratory, together with all other specimens, until time of testing. In table 4 the measured compressive strength is presented for the different concrete recipes as well as at different age.

Table 4. Concrete strength (MPa).

	7 days	28 days	Day of fire test
w/p=0.30	58.9	72.3	77.8
	61.6	72.3	78.6
	59.8	70.5	78.4
Mean	**60.1**	**71.7**	**78.3**
w/p=0.40 no fibres	42.9	57.1	59.4
	43.3	54.5	61.1
	43.3	54.0	59.6
Mean	**43.2**	**55.2**	**60.0**
w/p=0.40 with fibres	36.2	50.9	58.0
	41.1	53.6	57.9
	37.1	56.3	59.9
Mean	**38.1**	**53.6**	**58.6**
w/p=0.55	27.2	33.9	37.1
	27.2	33.5	36.5
	22.3	33.0	37.4
Mean	**25.6**	**33.5**	**37.0**

The moisture content of the specimens was measured on the same cubes as used for measurement of compressive strength after 3 months. The cubes were weighed after the compressive tests and then placed in an oven. They were dried in 105 ºC for 30 days and thereafter weighed again. The determined moisture content is presented in table 5.

Table 5. Measured moisture content (percent by weight).

	Moisture content
w/p=0.30	4.78
	4.92
	4.90
Mean	**4.87**
w/p=0.40 no fibres	4.95
	5.17
	5.20
Mean	**5.11**
w/p=0.40 with fibres	4.74
	4.83
	4.95
Mean	**4.84**
w/p=0.55	5.32
	5.11
	5.11
Mean	**5.18**

2.1.2 Tunnel concrete

Six different concrete recipes were meant to be used. In the first casting it was necessary to use a large quantity of superplastiziser. This lead to “bubbling” of the concrete, i.e. lots of bubbles were formed on the surface. Hence the concrete recipes were remade so that the water content was increased. The problem aroused again when using fibres of polypropylene. These fibres attract water which in turn affects the consistency of the concrete.

The final concrete recipes that were used in the production of the test specimens are shown in table 6. All concrete had the same water-cement ratio, w/c-ratio = 0.38. The w/c-ratio of the concrete including silica was calculated as follows:

$$w/c = \frac{W}{C + 2 \cdot S}$$

where *W* is the amount of water, *C* is the amount of cement and *S* is the amount of silica in kg/m^3. Two different plastisizers were used, Glenum 51 and Peramin F. In the concretes named E and F was a lime filler used designated Limus 40. Polypropylene fibres were used in concretes B, D and F. The fibres were designated Fibrin and had a diameter of 18 µm.

Table 6. Concrete recipes.

	Recipe A	Recipe B	Recipe C	Recipe D	Recipe E	Recipe F
Cement (kg/m^3)	420	450	405	425	445	470
Silica (kg/m^3)	-	-	25	25	-	-
0-8 mm (kg/m^3)	965	940	943	919	900	869
8-16 (kg/m^3)	174	170	170	165	144	140
16-32 (kg/m^3)	682	664	667	650	644	625
Glenum 51 (kg/m^3)	2.0	2.0	2.0	2.0	2.3	2.0
Peramin F (kg/m^3)	1.0	1.0	0.75	1.0	0.75	1.0
Limus 40 (kg/m^3)	-	-	-	-	100	100
Fibrin (kg/m^3)	-	2.0	-	2.0	-	2.0
Water (kg/m^3)	159	171	171	180	171	180

Ballast Väst AB in Borås manufactured the concrete. They also assisted in the development of the concrete recipes. The concrete was mixed at Ballast Väst AB and thereafter transported to SP for casting.

When manufacturing concrete C, 1.5 kg/m^3 Glenum 51 was used. After transportation to SP the concrete was too stiff for casting and another 0.5 kg/m^3 Glenum 51 was added to the concrete in the concrete mixer. The same occurred with concrete E where 1.5 kg/m^3 Glenum 51 was used when manufactured and an additional 0.5 kg/m^3 Glenum 51 was added at SP. The amounts of plastizisers given in table 6 is the total amount, i.e. including the additional amount added at SP.

The casting was made during the period March 4, 2003 to April 9, 2003.

The consistency of the concrete was measured at the concrete factory. The slump values are shown in table 7. Note that the slump values for concrete recipes C and E were later modified since more plastiziser was added at SP. Thus the given values are not valid for those concretes.

Table 7. Slump measurements (mm).

	Concrete recipe					
	A	B	C	D	E	F
Before addition of fibres	180	230	160	230	220	235
After addition of fibres	-	55	-	75	-	105

The compressive strength of the concrete was measured in accordance with SS 13 72 10 with the deviation from the standard that the age of the concrete was approximately 4 months. Three cubes of each concrete recipe were tested. The results are presented in table 8. The results are presented as mean value for each recipe and standard deviation.

Table 8. Compressive strength of the different concrete recipes.

	Concrete recipe					
	A	B	C	D	E	F
Mean value (MPa)	106.9	104.7	72.9	88.1	103.2	94.2
Standard deviation (MPa)	2.5	0.7	0.8	1.4	2.1	2.7

The material from the cubes used for determination of compressive strength were used for measurement of moisture content. The moisture content was determined through weighing before and after drying. The drying was carried out in a oven with a temperature of 105 ºC during 7 days. The measured moisture content is given in table 9. The results are presented as mean value for each recipe and standard deviation.

Table 9. Moisture content of the different concrete recipes.

	Concrete recipe					
	A	B	C	D	E	F
Mean value (%)	3.7	4.2	4.0	4.9	4.2	4.8
Standard deviation (%)	0.0	0.1	0.0	0.0	0.1	0.2

2.2 Test specimens

2.2.1 Self-compacting concrete

Four slabs with the dimensions 1800 x 1200 x 200 mm^3 were manufactured, one of each recipe. The slabs were pre-stressed through 13 wires with a load of 55 kN each, i.e. a total load of 715 kN. The wires were placed 35 mm from the fire exposed surface of the slabs. Hence the theoretical compressive stress at the fire exposed surface was 8.8 MPa after casting. Drawings of the slabs are shown in figure 1. Photos of the manufacturing of the specimens are presented in Appendix D1.

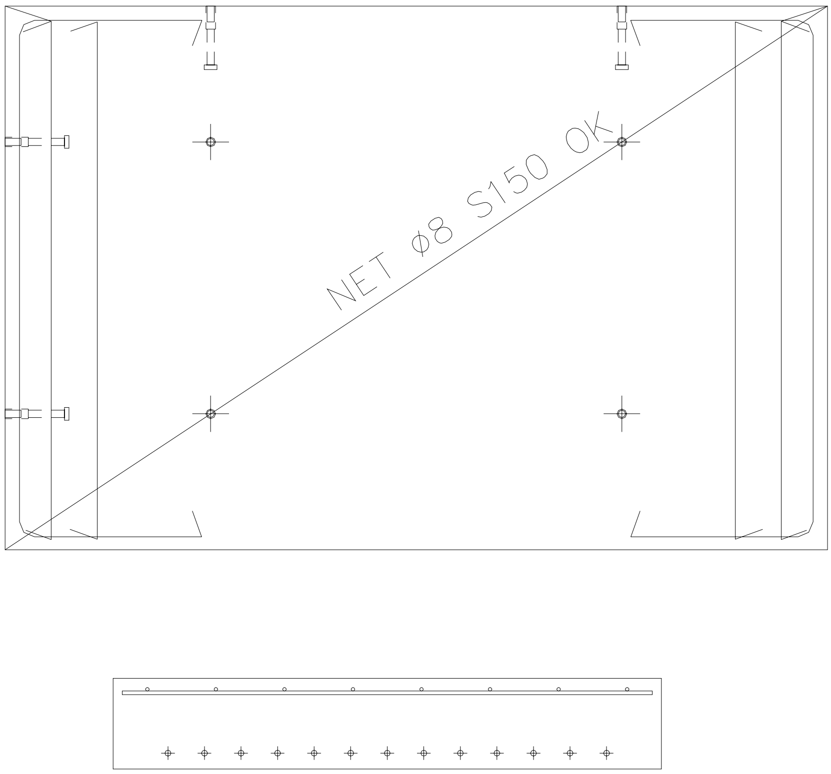

Figure 1. Design of large slabs.

Two beams with the dimensions 3600 x 600 x 200 mm^3 were manufactured of concrete with w/p = 0.40. One beam with fibres and one without fibres. Non-tensioned reinforcement was used in the beams, i.e. no pre-stressing was applied in the beams. The design of the beams are shown in figure 2.

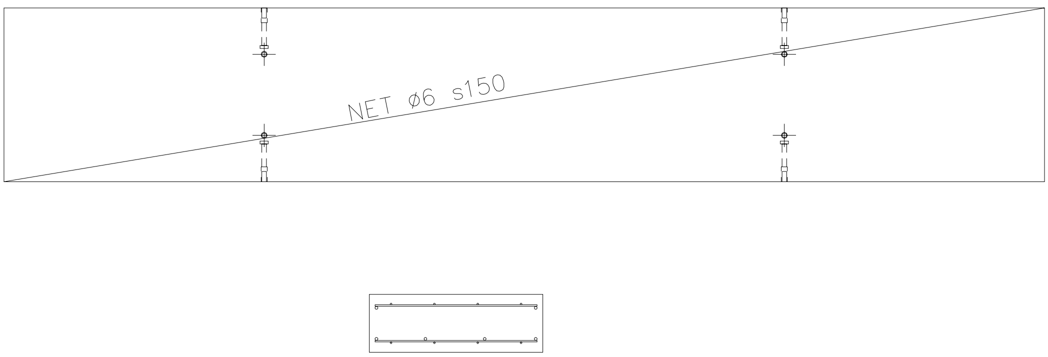

Figure 2. Design of large beams.

In addition to the large size specimens several small scale specimens were manufactured. Cylinders with a diameter of 150 mm and lengths 300 mm and 450 mm respectively. Small slabs with dimensions 600 x 500 x 200 mm^3 were also manufactured. The small specimens were all manufactured from all concrete recipes. Photos of the manufacturing of these specimens are presented in Appendix E1.

Table 10 gives an overview of all specimens manufactured of self-compacting concrete and used in fire tests. The specimens were delivered to SP in the beginning of October, 2003, and stored in the laboratory until testing. The mean temperature in the laboratory was 18 ºC and the mean relative humidity 55 % during this period.

Table 10. Test specimens.

Code	Geometry (mm)	w/p	Fibres (kg/m^3)	Spec	Stress type	Stress level (MPa)	Fire curve
LS3001	1800x1200x200	0.30	0	1	Pre-stress, comp	8.8	Std
LS4001	1800x1200x200	0.40	0	1	Pre-stress, comp	8.8	Std
LS4011	1800x1200x200	0.40	1	1	Pre-stress, comp	8.8	Std
LS5501	1800x1200x200	0.55	0	1	Pre-stress, comp	8.8	Std
LB4001	3600x600x200	0.40	0	1	External bending	7.7	Std
LB4011	3600x600x200	0.40	1	1	External bending	7.7	Std
SS3001-SS3002	600x500x200	0.30	0	2	Non	0	Std
SS3003-SS3004	600x500x200	0.30	0	2	External comp	2.5	Std
SS4001-SS4002	600x500x200	0.40	0	2	Non	0	Std
SS4003-SS4004	600x500x200	0.40	0	2	External comp	2.5	Std
SS4011-SS4012	600x500x200	0.40	1	2	Non	0	Std
SS4013-SS4014	600x500x200	0.40	1	2	External comp	2.5	Std
SS5501-SS5502	600x500x200	0.55	0	2	Non	0	Std
SS5503-SS5504	600x500x200	0.55	0	2	External comp	2.5	Std
LC3001-LC3002	∅ 150, l=450	0.30	0	2	Non	0	Std
LC3003-LC3004	∅ 150, l=450	0.30	0	2	External comp	5.3	Std
LC4001-LC4002	∅ 150, l=450	0.40	0	2	Non	0	Std
LC4003-LC4004	∅ 150, l=450	0.40	0	2	External comp	5.3	Std
LC4011-LC4012	∅ 150, l=450	0.40	1	2	Non	0	Std
LC4013-LC4014	∅ 150, l=450	0.40	1	2	External comp	5.3	Std
LC5501-LC5502	∅ 150, l=450	0.55	0	2	Non	0	Std
LC5503-LC5504	∅ 150, l=450	0.55	0	2	External comp	5.3	Std

The manufacturing of the test specimens was performed at Skanska Prefab in Strägnäs, Sweden, during September 25-26, 2003 and transported to SP in Borås, Sweden, September 30, 2003.

2.2.2 Tunnel concrete

Six different specimen types (geometries) were manufactured ranging from small cubes up to large slabs. The number of specimens for each geometry as well as recipe is presented in table 11. Photos of the manufacturing of the specimens are presented in Appendix F1.

Table 11. Geometry and number of test specimens.

Type of specimen	Number of specimens per recipe					
	A	B	C	D	E	F
Slab 1800 x 1200 x 400 mm	2	2	2	2	2	2
Cube 150 x 150 x 150 mm	9	9	9	9	9	9
Column 200 x 200 x 1000 mm	2	-	2	2	-	-
Cylinder Ø 150, length 300 mm	3	3	3	3	3	3
Cylinder Ø 150, length 450 mm	2	-	2	2	-	-
Small slab 500 x 500 x 100 mm	3	3	3	3	3	3

Only four specimens of the small cubes of each recipe were used in the fire tests. Three cubes of each recipe were used for measurements of strength and moisture content, and two cubes for measurement of thermal properties which will not be covered by this report.

The large slabs were reinforced in a grid with Ø 12 mm bars. The reinforcement cover was 50 mm, see figure 3. The distance blocks used were made of concrete. In addition to the non-tensioned reinforcement, plastic tubes with an inner diameter of 28 mm were placed longitudinally in the form. Five tubes were used in each specimen, with a distance of 240 mm between the tubes. Before the testing steel bars were placed in the tubes in which a pre-stress were applied.

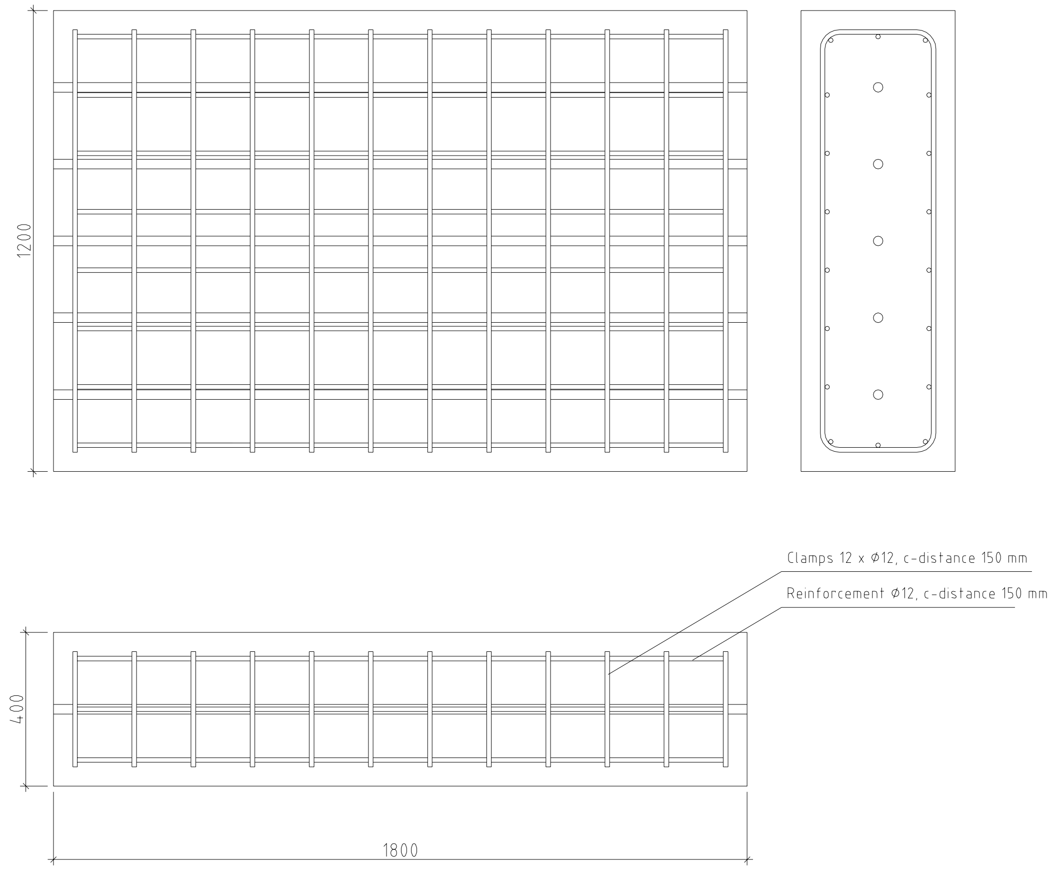

Figure 3. Reinforcement in slabs.

The columns were reinforced as shown in figure 4. The cover of the reinforcement was 50 mm.

All specimens were numbered in accordance with table 12. The cubes numbered x3-x5 were used for measurement of strength and moisture content. The cubes numbered x6-x9 were used in the fire tests.

Table 12. Name of test specimens.

Type of specimen	Concrete recipe					
	A	B	C	D	E	F
Large slab	A1-A2	B1-B2	C1-C2	D1-D2	E1-E2	F1-F2
Cube	A3-A9	B3-B9	C3-C9	D3-D9	E3-E9	F3-F9
Column	A10-A11	-	C10-C11	D10-D11	-	-
Short cylinder	A18-A20	B18-B20	C18-C20	D18-D20	E18-E20	F18-F20
Long cylinder	A12-A14	-	C12-C14	D12-D14	-	-
Small slab	A21-A23	B21-B23	C21-C23	D21-D23	E21-E23	F21-F23

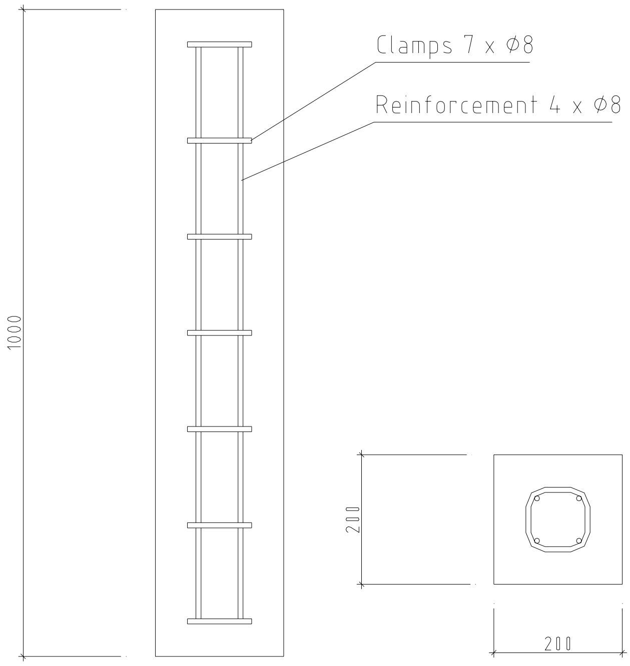

Figure 4. Reinforcement in columns.

All large slabs were fire tested under mechanical loading. The loads were applied through pre-stressing. Steel bars were placed in the specimens in the longitudinal direction, see figures 5 and 6. The bars passed through two specimens and thus a coupling was made between these two specimens. Between the specimens a rock wool insulation designated Isover Takboard with thickness 20 mm was placed. In each pair of coupled specimens 5 steel bars with diameter 25 mm were applied. Each steel bar was loaded in tension with a force of 200 kN, which gives a total compressive force in the concrete of 1000 kN. This force corresponds to a compressive stress in the longitudinal direction of 2.1 MPa.

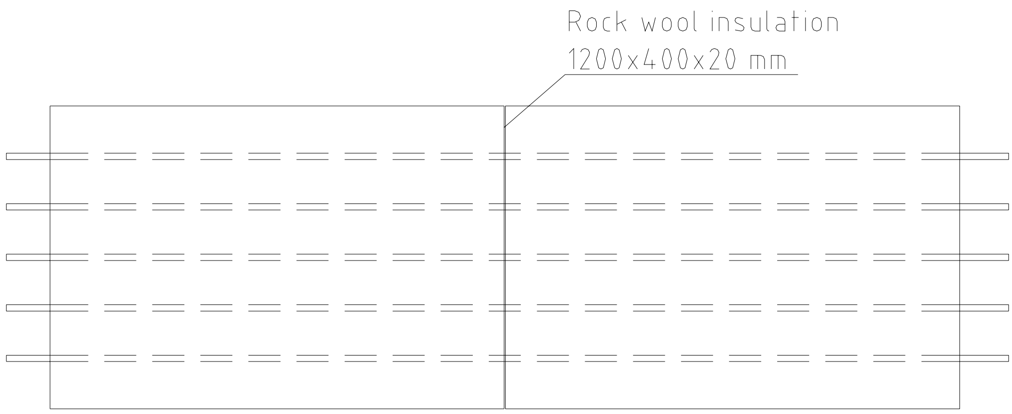

Figure 5. Coupling of two specimens with pre-stressed steel bars.

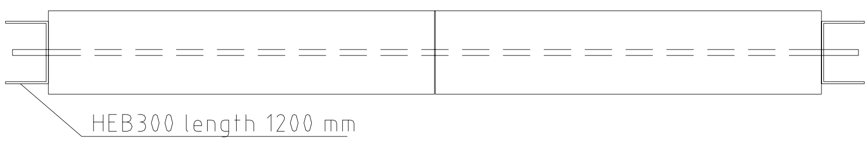

Figure 6. Load distribution with HEB300 steel beams.

In order to distribute the load over the specimen surface a 1200 mm long steel beam designated HEB300 was placed on each side, see figure 4.

The pre-stress was applied approximately 30 minutes before the commencement of the fire tests. On some of the steel bars load cells were attached in order to monitor the level of the pre-stress. The level of the pre-stress was monitored during the whole duration of the fire tests. Figure 7 shows on which steel bars the load cells were attached. At the first fire tests load cells 1 and 2 were used to measure the loads in specimens E1 and F1, load cell 3 in specimens C1 and D1, and load cell 4 in specimens A1 and B1. At the second fire tests load cells 1 and 2 were used to measure the loads in specimens D2 and F2, load cell 3 in specimens B2 and C2, and load cell 4 in specimens A2 and B2.

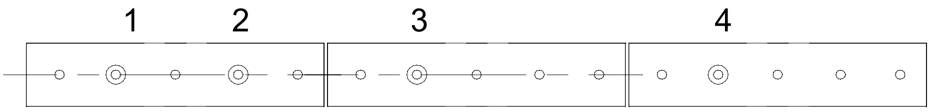

Figure 7. Placement of load cells in the fire tests.

The casting of the test specimens took place during the period March 4, 2003 to April 9, 2003. Some days after casting the specimens were placed in a container filled with water. The container was placed in a conditioning chamber with constant temperature of 20°C. Hence all specimens were cured under water. During the time between casting and water storage the specimens were covered with a plastic foil. Dates for casting and water storage are shown in table 13.

Table 13. Dates of casting and water storage.

	Casting	Water storage
Concrete A, B	March 4, 2003	March 6, 2003
Concrete C, D	March 14, 2003	March 18, 2003
Concrete E, F	April 9, 2003	April 11, 2003

All specimens were removed from the water storage June 10, 2003. Thereafter the specimens were stored in the fire laboratory until testing. The mean temperature in the laboratory was 21 °C and the mean relative humidity 59 % during this time.

2.3 Instrumentation

2.3.1 Self-compacting concrete

The large specimens were equipped with thermocouples mounted at different locations within the concrete. On each of the large slabs 20 thermocouples were mounted. They were located to the quarter points of the fire exposed surface of the specimens. At each location 5 thermocouples were mounted at different depths from the fire exposed surface, 10 mm, 25 mm, 50 mm, 100 mm and 200 mm (i.e. on the unexposed surface). The locations of the thermocouples are shown in figure 8.

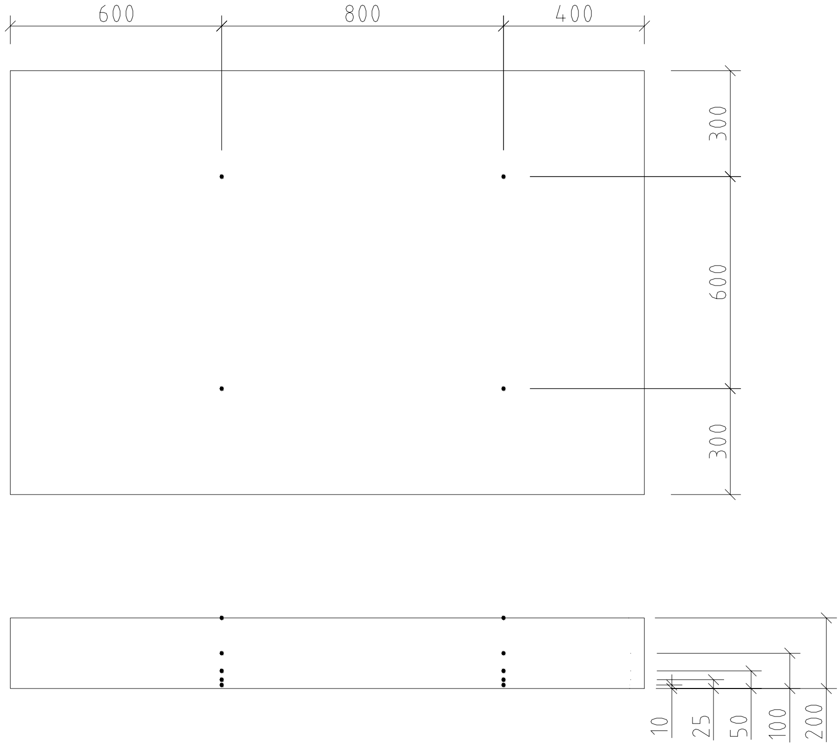

Figure 8. Positions of thermocouples within and on the large slabs.

A total of 21 thermocouples were mounted in and on the large beams. In addition to measure the temperature profile through the cross-section of the beam also the effect of the boundary was determined. The location of the thermocouples is shown in figure 9.

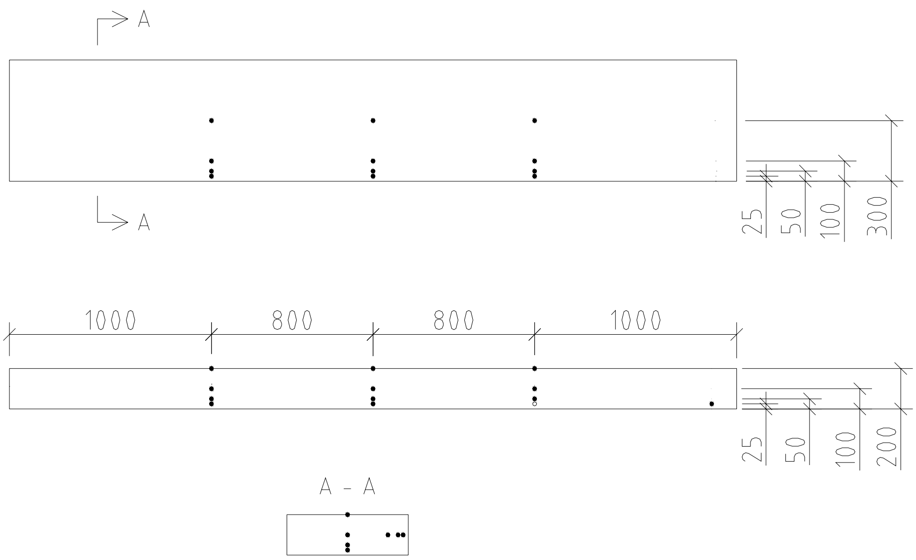

Figure 9. Positions of thermocouples within and on the large beams.

The small scale slabs were also instrumented with thermocouples within the specimens. Two thermocouples were mounted centrally placed on the slabs at a depth of 25 mm and 50 mm from the fire exposed surface.

2.3.2 Tunnel concrete

The temperature in the large slabs as well as in the columns at different depths and positions was measured. The placement of the thermocouples in the slabs is shown in figure 10. In each of the columns two thermocouples were mounted centrally at a depth of 50 mm and 100 mm respectively.

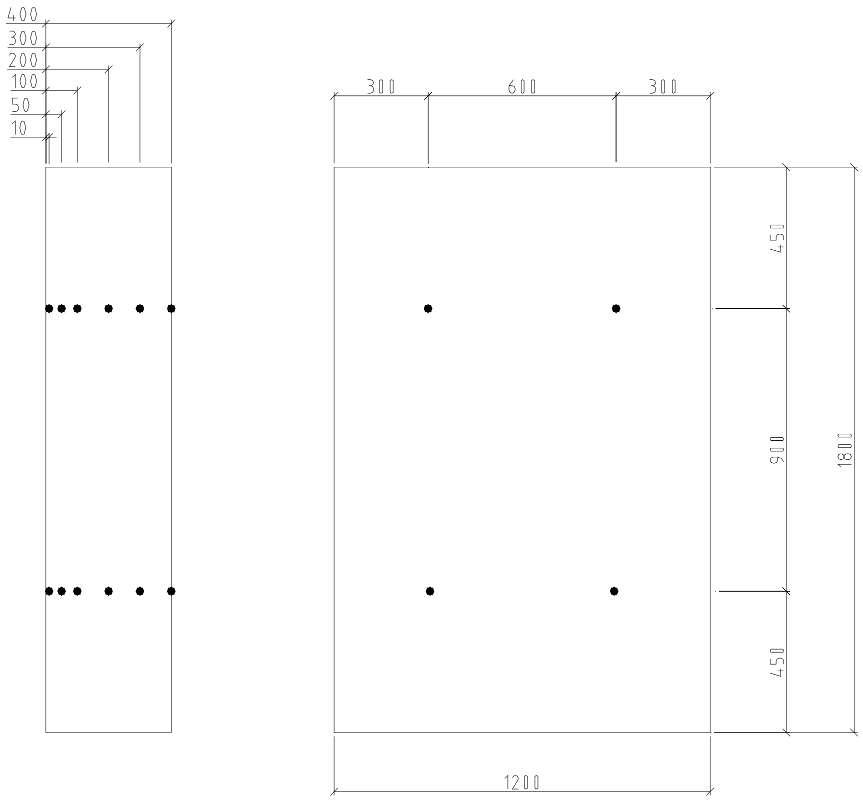

Figure 10. Positions of thermocouples within and on the large slabs.

The thermocouples mounted on the unexposed surface of the large slabs were designed as prescribed by the test standard. The thermocouples mounted within the test specimens had a quick-tip mounted at the measuring point. These thermocouples were mounted in the mould before casting. No thermocouples were placed in direct contact with the reinforcement.

3 Test procedure

3.1 Large furnace tests of self-compacting concrete

The large slabs and beams as well as the long cylinders of self-compacting concrete were tested in one furnace test. The large slabs and beams were placed on top of the furnace while the long cylinders were placed 200 mm up from the floor of the furnace, see figures 11 and 12. Between each pair of slabs and the beams were concrete planks placed to cover the furnace. These planks were also used as support for the large slabs. The temperature in the furnace was measured with 13 plate thermometers, 11 placed 100 mm below the large slabs or beams, and two at a height equal to the centre of the cylinders.

The large beams were externally loaded with two line loads to a level of 100 kN/m which gave a maximum bending stress of 16.5 MPa. The load was applied by two cylinders at each line and the load was distributed to a line load by steel beams designated HEB 100. A ceramic insulation was placed between the specimen and the steel beam. The load was applied 30 minutes before the fire test started.

The large slabs did not have any external loads. They were supported by steel beams designated HEB 100 which were loosely fastened in the lifting devices as shown in figure 11.

Between the specimens, and between specimen and concrete planks a rock wool was insulation placed.

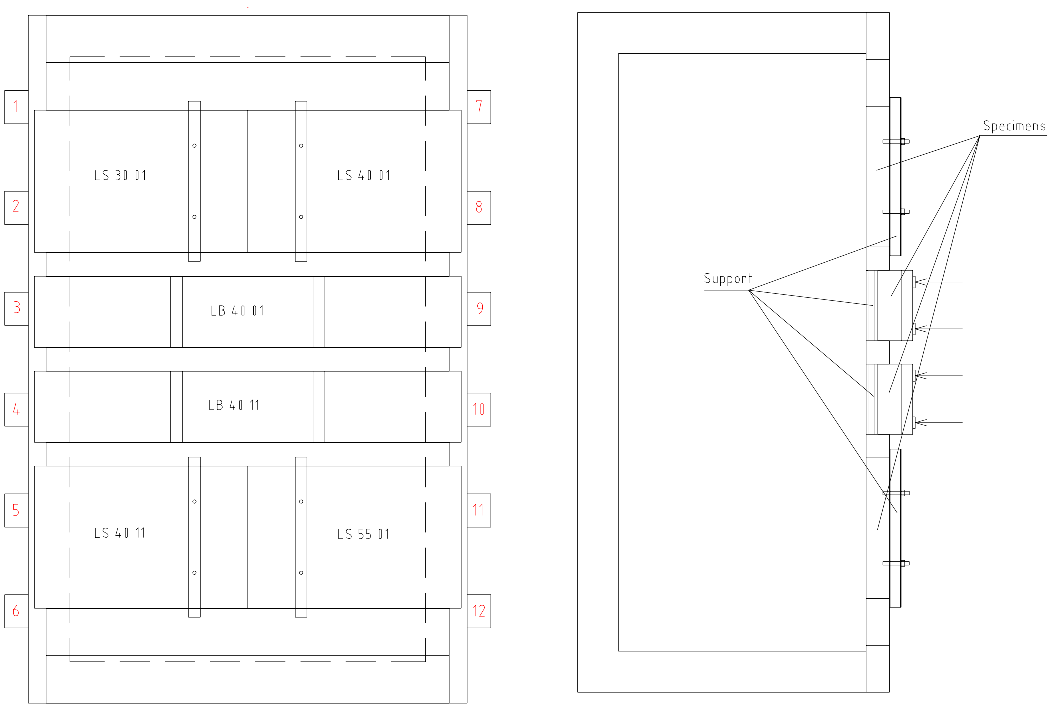

Figure 11. Placement of large slabs and beams on the horizontal furnace.

Four long cylinders were tested for each concrete recipe. Of these were two loaded in compression and two were unloaded. The load was applied through a threaded bar going through a centrally mounted pipe in the specimens. The threaded bar had a diameter of 24 mm and the load was applied by using a dynamometric wrench to a moment of 400 Nm.

This equals a compressive stress of 5.3 MPa. The cylinders with the last digit of the code equal to 3 and 4 were loaded.

The loaded cylinders were all covered with a rock wool insulation at the end where the nut was applied. The insulation covered 50 mm of the end of the specimen and the threaded bar as well as the nut in order not to loose the load when heated. However it was not possible to check whether the load was on during the fire test or not. The cylinders were placed in a cradle on the floor of the furnace, see figure 12.

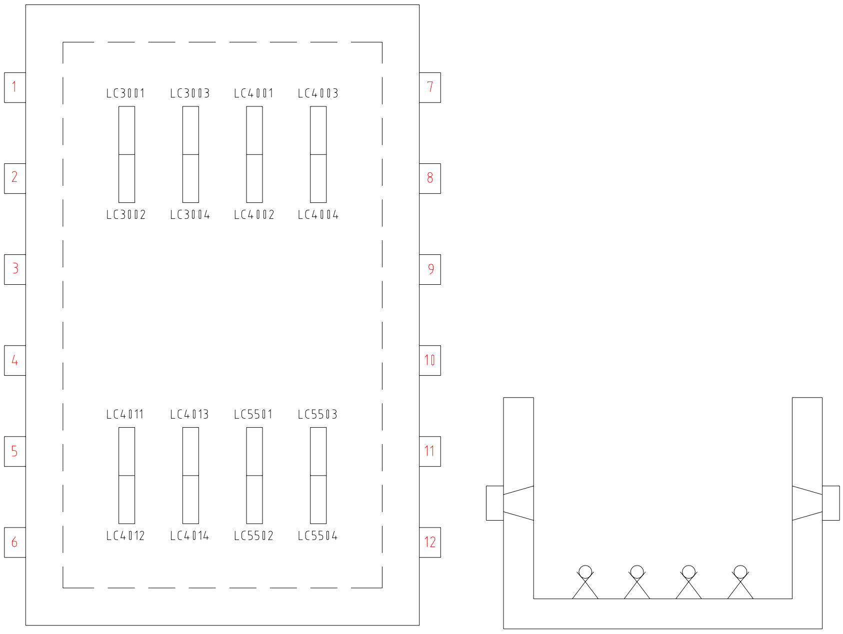

Figure 12. Position of long cylinders in the horizontal furnace.

During the fire test the specimens were observed through windows in the furnace. Hence it was possible to visually observe the spalling. Although it was difficult to continuously observe all specimens. Thus the visual observations registered do not cover everything that happened with the specimens during the test.

Temperatures in the furnace as well as the temperature on and in the specimens were registered during the whole test. The temperature on and in the specimens was also registered for an additional 120 minutes after the fire test was finished.

3.2 Large furnace tests on tunnel concrete

The large slabs were placed on a horizontal furnace. Between each pair of slabs a concrete beam with a width of 400 mm was placed. Between the slabs and the concrete beam a board of rock wool insulation was positioned.

The columns were hanging from the concrete beams through a threaded bar. Between the columns and the concrete beam as well as under the column ceramic insulation was attached.

In the first furnace test several small specimens were placed at the bottom of the furnace. The position of specimens is shown in figures 13-14.

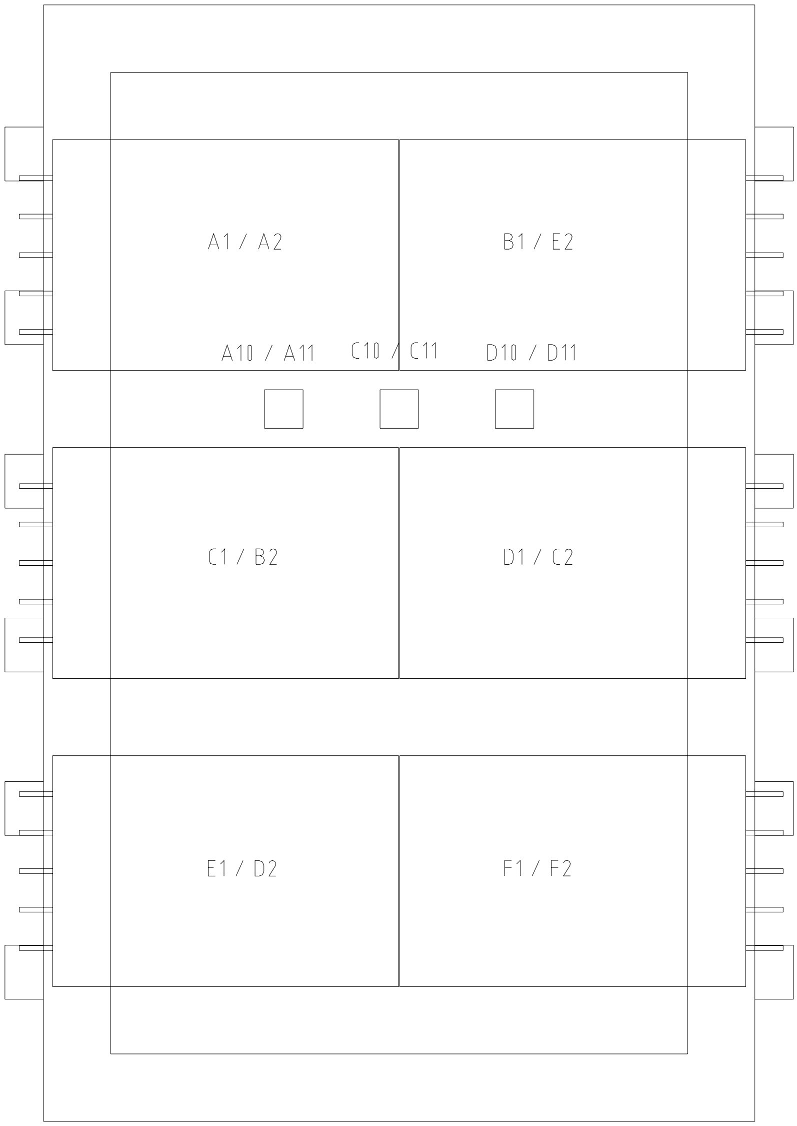

Figure 13. Position of large slabs and columns on the furnace.

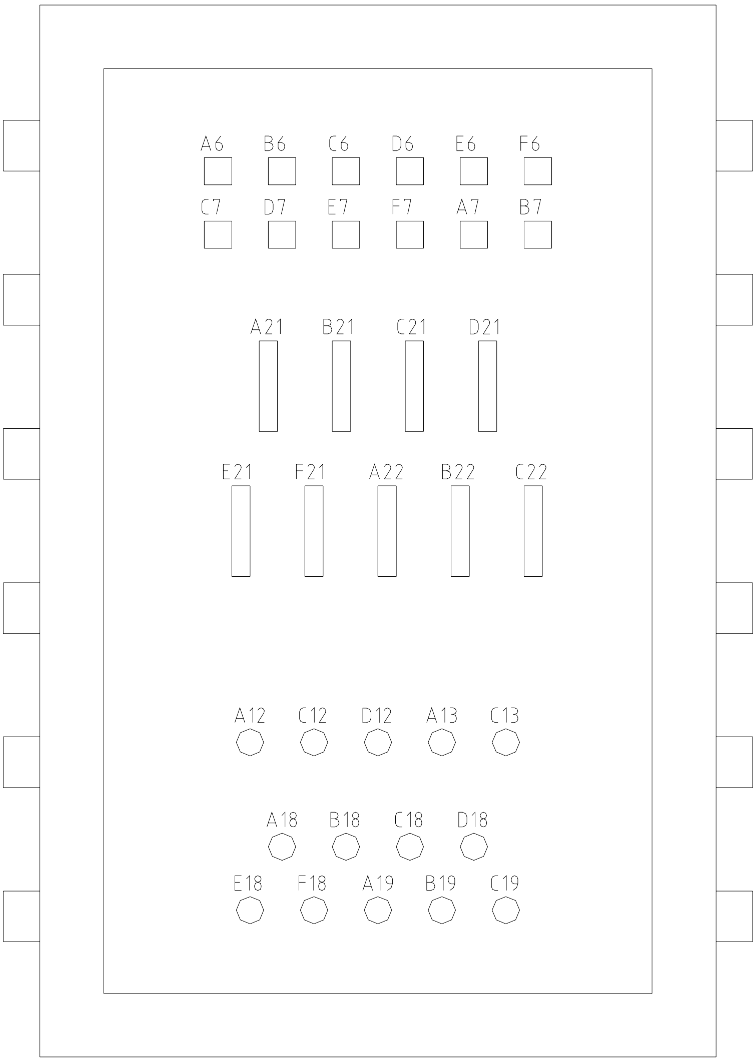

Figure 14. Position of small specimens on the furnace floor.

3.3 Small furnace tests on self-compacting concrete

Four specimens of each concrete recipe were tested on the small furnace. Two specimens were tested unloaded and the remaining two were loaded in compression during the fire test. The specimen was placed on the furnace giving an fire exposed area of 360 x 450 mm. At the boundary the specimen was placed on rock wool insulation, see figure 15.

The load was applied through 16 mm threaded bars going through a steel profile mounted on the short sides of the specimens. A total of four bars was used and each bar was loaded by using a dynamometric wrench to a moment of 200 Nm, which equals 62 kN. The compressive stress in the slabs was thus 2.5 MPa. The small slabs with the last digit of the code equal to 3 and 4 were loaded.

The specimens were weighed before and after the fire test. After the fire test the spalling depth was measured in a 100 x 100 mm grid.

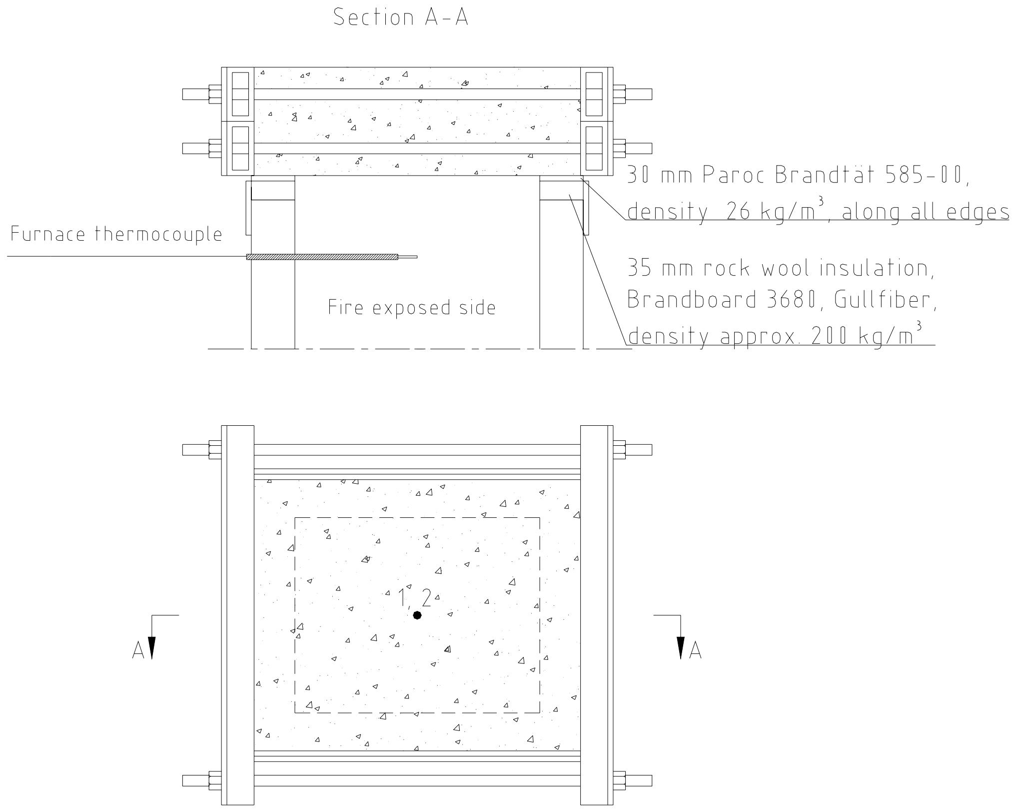

Figure 15. Test set-up used in the small scale furnace tests on self-compacting concrete.

3.4 Small furnace tests on tunnel concrete

One or two specimens of each concrete recipe were tested on the small furnace. Only one specimen was tested of recipes A, B and C, while two specimens were tested for recipes D, E and F. All tested specimens were loaded during the fire tests. The specimen was placed on the furnace giving an fire exposed area of 360 x 450 mm. At the boundary the specimen was placed on rock wool insulation, see figure 16.

The load was applied through 16 mm threaded bars going through a steel profile mounted on the short sides of the specimens. A total of two bars was used and each bar was loaded by using a dynamometric wrench to a moment of 150 Nm, which equals 51 kN. The compressive stress in the slabs was thus 2.5 MPa.

The specimens were weighted before and after the fire test. After the fire test the spalling depth was measured in a 100 x 100 mm grid.

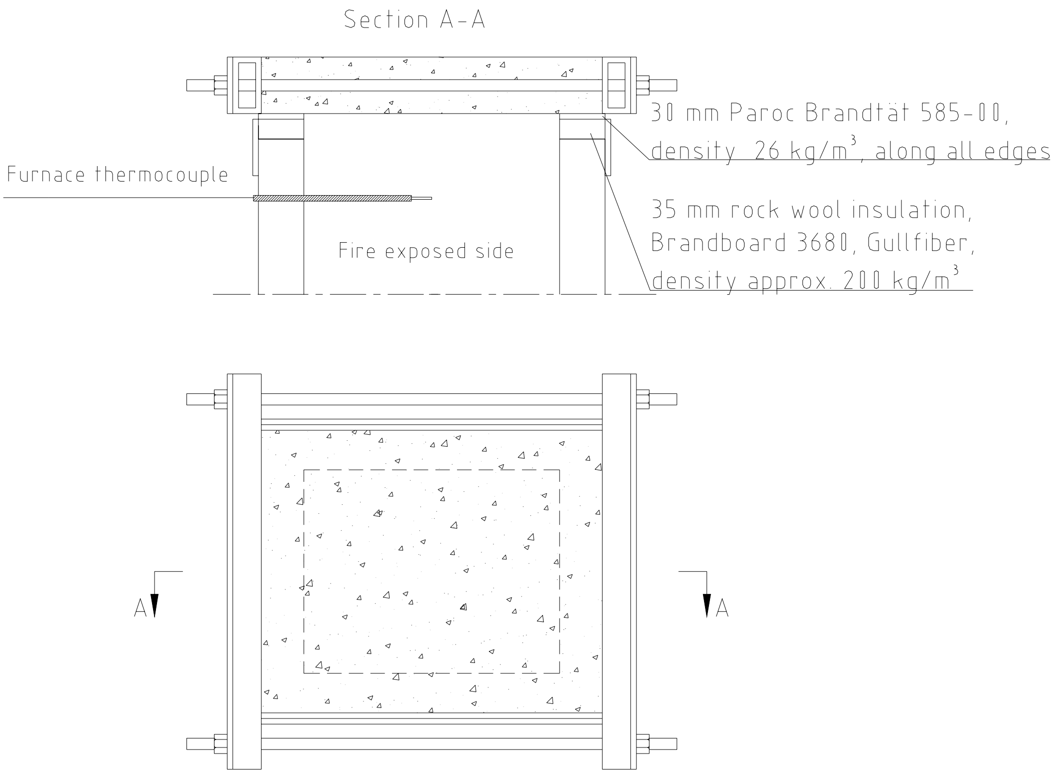

Figure 16. Test set-up used in the small scale furnace tests on tunnel concrete.

3.5 Tests made at DTU

One cylinder of each concrete recipe of the tunnel concretes was sent to the Danish Technical University for spalling tests on their own designed apparatus. A schematic design of the apparatus is shown in figure 17.

The cylindrical test specimen is placed in the iron muff after which the specimen is restrained by tightening the bolts to a selected moment, i.e. a selected stress level. Hereafter the temperature loggings are started and exposure begins. Exposure takes place for 60 minutes. The temperature in the furnace is kept constant at 1000 ºC during this period.

The spalling is measured as the weight of the spalled material.

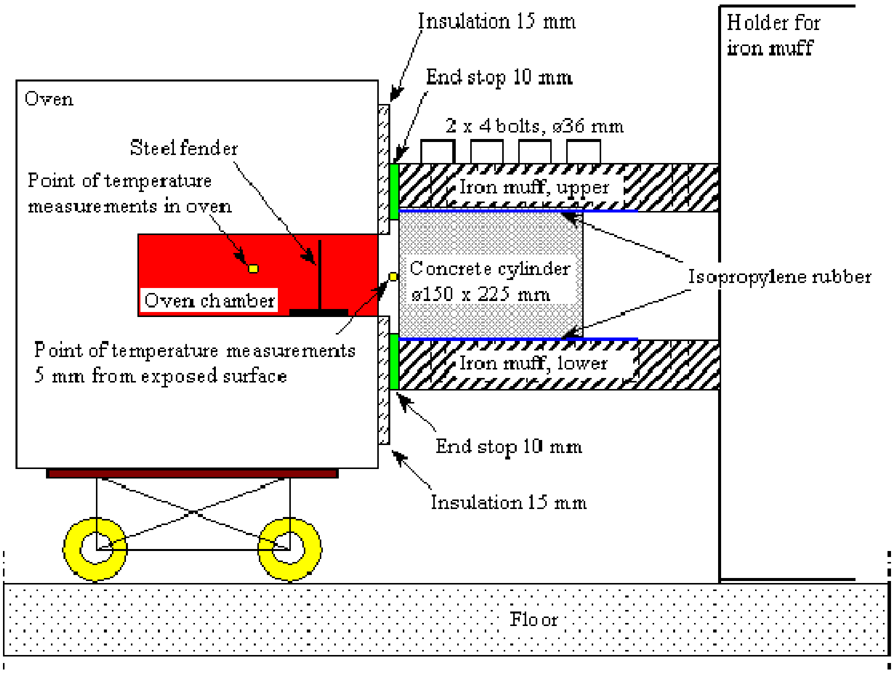

Figure 17. Experimental set-up (Jensen, 2003)

3.6 Spalling measurements

The fire spalling on the specimens tested at SP was measured using two different methods. One through weighing and one by measuring the actual depth of the scaled off material from the specimens. When measuring the spalling by weighing the weight loss was calculated as:

$$weightloss = \left(1 - \frac{m_{after}}{m_{before}\left(1 - u/(1+u)\right) - m_{fibres}}\right) \cdot 100\ \%$$

where m_{before} is the weight of the test specimen before the fire test, m_{fibres} is the weight of fibres, u is the moisture content, and m_{after} is the weight of the test specimen after the fire test. The moisture content used in the calculations was not the same as the moisture content measured on the separate cubes. When fire testing concrete, some of the free water as well as some of the hydrate water will evaporate. It has not been possible to determine any exact value on how much of the water that has evaporated during the fire test. Instead the moisture content was fitted in the calculation in such way that for specimens without any visible spalling the weight loss was set to zero. This will not give a correct value for all specimens since the evaporated water content may vary. Although, it will give a relative good estimate of the weight loss.

When measuring the depth of the scaled off material a sliding calliper was used. A steel frame was mounted on the fire exposed surface of the specimen which was used as a reference when measuring the spalling depth. The spalling was measured in a grid with a spacing of 100 mm. Due to the strong influence of the boundary only measurements taken at least 300 mm from the boundary have been included. The results are presented as a mean spalling depth, the maximum spalling depth, and a characteristic spalling depth. The characteristic spalling depth was calculated as the upper 95 % fractile assuming a normal distribution.

4 Test results

4.1 Large furnace test on self-compacting concrete

4.1.1 General information

The test was carried out December 16, 2003. The duration of the fire exposure was 61 minutes. The furnace temperature and pressure were controlled in accordance with EN 1363-1. Temperatures in the concrete were measured during the test and the measured temperatures are presented in Appendix B.

4.1.2 Furnace temperature

The temperature in the furnace during the fire test is presented in figures 18 and 19. The test stopped after 61 minutes, but the data acquisition was kept running for an extra 75 minutes.

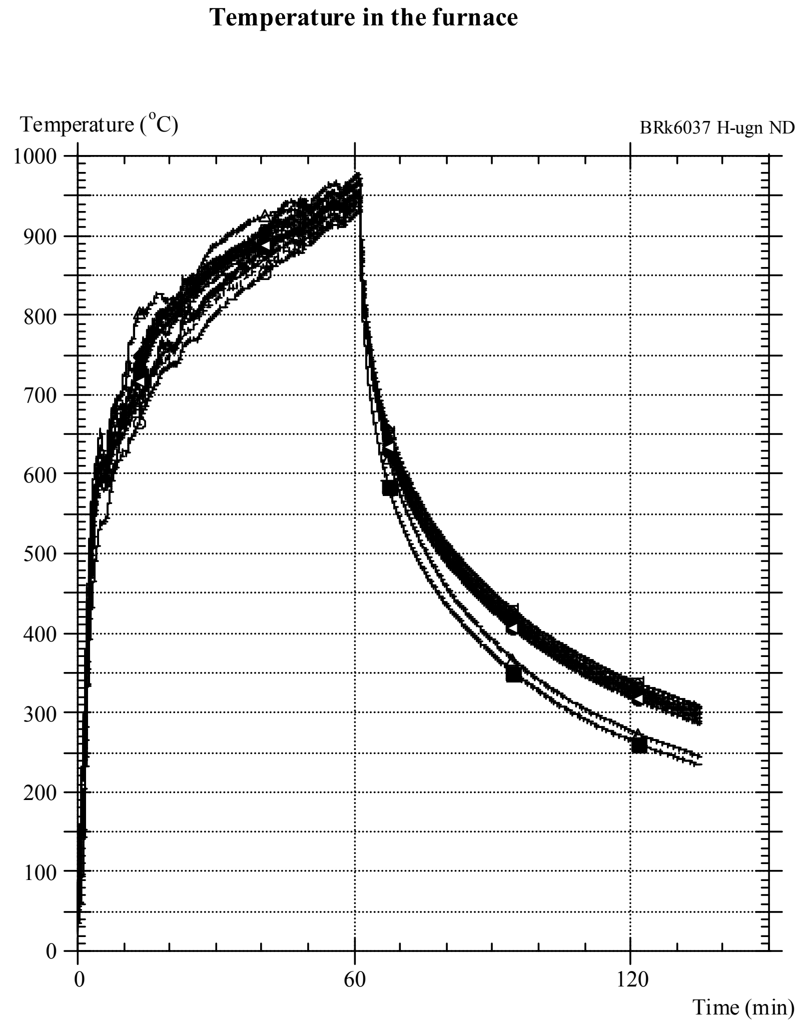

Figure 18. Temperature measured in the furnace during the fire test.

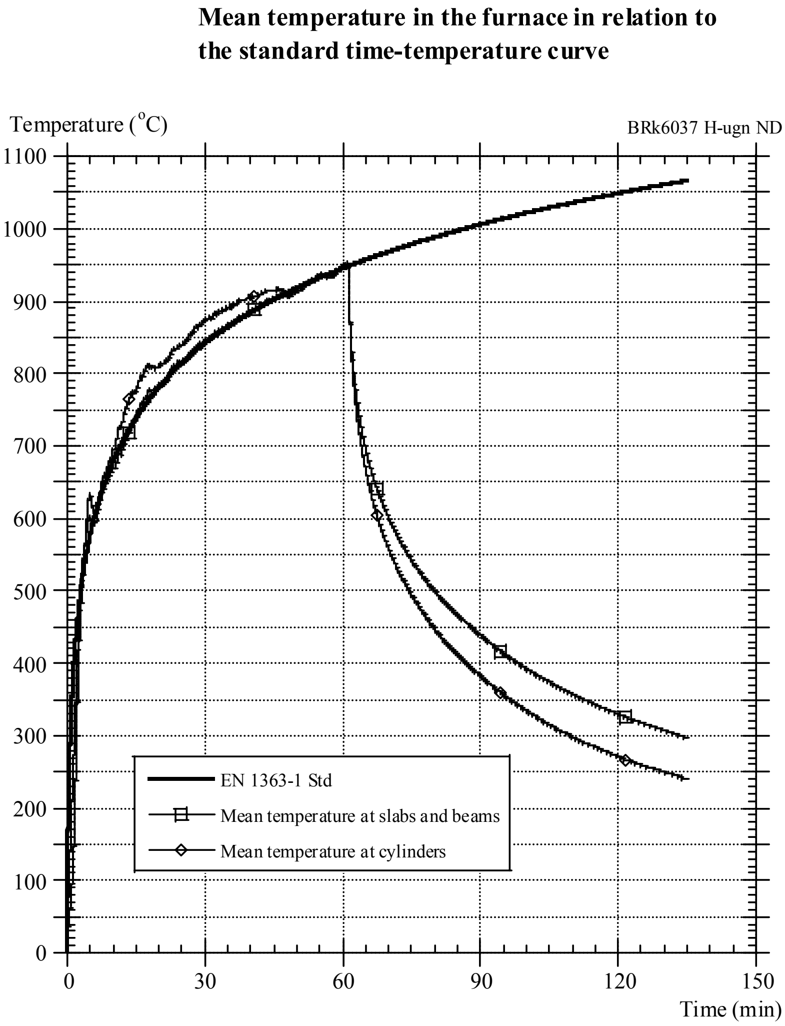

Figure 19. Mean temperature in relation to the standard time-temperature curve.

4.1.3 Pressure

The pressure in the furnace was during the fire exposure measured 250 mm below the surface of the large slabs and controlled to a level of 17.5 Pa. This corresponds to an overpressure of 20 Pa 100 mm below the surface of the specimens. The measured pressure is shown in figure 20.

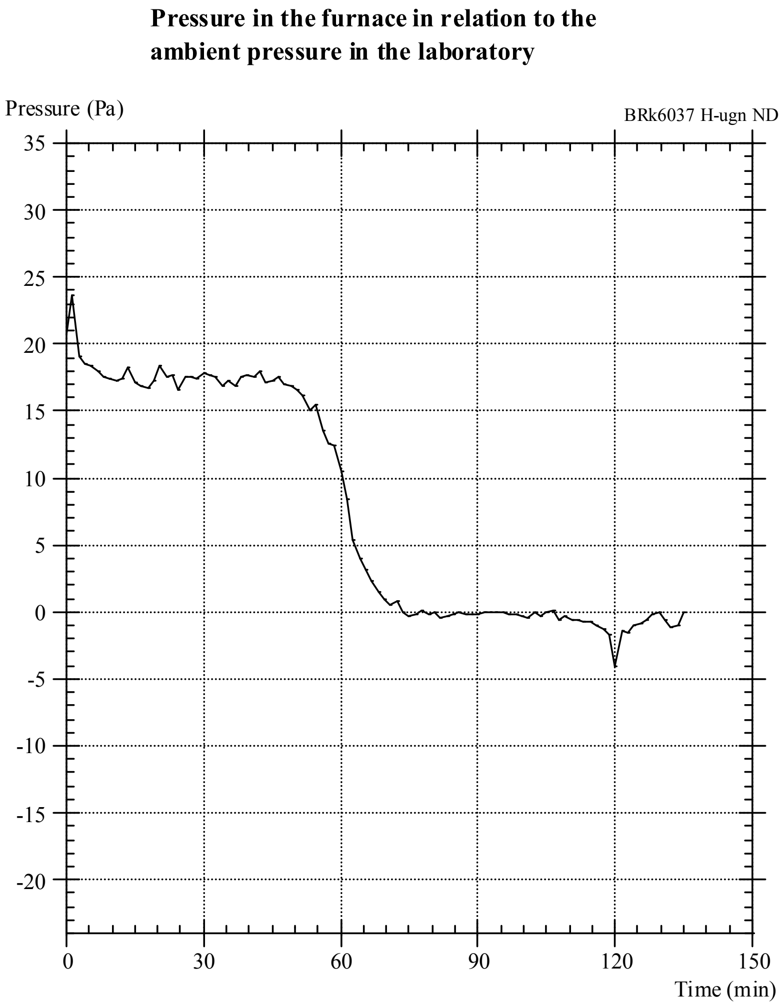

Figure 20. Pressure in the furnace in relation to the ambient pressure in the laboratory.

4.1.4 Spalling

4.1.4.1 Large slabs

The amount of spalling of the large slabs is shown in table 14. It shall be noted that when calculating the weight loss the amount of evaporated water was estimated to 2.8 % which is the amount giving 0 % weight loss for specimen LS 40 11.

The large slabs were loaded through pre-stressed wires. It was thus not possible to determine the load level during the fire test. Since there was extensive spalling on some specimens and the concrete layer covering the wires spalled of, the loading was most certainly lost after some time during the fire test. Hence, the amount of spalling for these specimens was probably less than if the load had been maintained during the entire test.

Table 14. Test results large slabs.

Code	w/p	Fibres (kg/m^3)	Stress type	Stress level (MPa)	Fire curve	Mean spalling (mm)	Max spalling (mm)	Charact spalling (mm)	Weight loss (%)
LS3001	0.30	0	Pre-stress, comp	8.8	Std	45	65	57	15.8
LS4001	0.40	0	Pre-stress, comp	8.8	Std	45	67	56	18.7
LS4011	0.40	1	Pre-stress, comp	8.8	Std	0	0	0	0.0
LS5501	0.55	0	Pre-stress, comp	8.8	Std	48	68	62	15.3

4.1.4.2 Large beams

The amount of spalling of the large beams is shown in table 15. It shall be noted that when calculating the weight loss, the amount of evaporated water was estimated to 2.5 % which is the amount giving 0 % weight loss for specimen LB 40 11.

Table 15. Test results large beams.

Code	w/p	Fibres (kg/m^3)	Stress type	Stress level (MPa)	Fire curve	Mean spalling (mm)	Max spalling (mm)	Charact spalling (mm)	Weight loss (%)
LB4001	0.40	0	External bending	7.7	Std	8	40	21	3.1
LB4011	0.40	1	External bending	7.7	Std	0	0	0	0.0

4.1.4.3 Long cylinders

The amount of spalling of the cylinders is shown in table 16. It shall be noted that when calculating the weight loss, the amount of evaporated water was estimated to 8.0 % which is the amount giving 0 % weight loss for specimen LC 40 13.

Table 16. Test results long cylinders.

Code	w/p	Fibres (kg/m^3)	Stress type	Stress level (MPa)	Fire curve	Weight loss (%)
LC3001	0.30	0	Non	0	Std	1.6
LC3002	0.30	0	Non	0	Std	2.2
LC3003	0.30	0	External comp	5.3	Std	17.8
LC3004	0.30	0	External comp	5.3	Std	19.4
LC4001	0.40	0	Non	0	Std	2.1
LC4002	0.40	0	Non	0	Std	4.8
LC4003	0.40	0	External comp	5.3	Std	23.4
LC4004	0.40	0	External comp	5.3	Std	21.4
LC4011	0.40	1	Non	0	Std	1.6
LC4012	0.40	1	Non	0	Std	2.0
LC4013	0.40	1	External comp	5.3	Std	0.0
LC4014	0.40	1	External comp	5.3	Std	0.3
LC5501	0.55	0	Non	0	Std	1.6
LC5502	0.55	0	Non	0	Std	4.0
LC5503	0.55	0	External comp	5.3	Std	19.3
LC5504	0.55	0	External comp	5.3	Std	14.7

4.1.5 Loading

The large slabs were loaded through pre-stressing. The wires were placed relatively close to the fire exposed surface. The covering was 35 mm only. Hence the stress in the wires would decrease when the wires were heated. For specimens LS3001, LS4001 and LS5501, i.e. the large slabs, the temperature exceeded 600 ºC after approximately 20 minutes. Thus the compressive stress introduced in the slabs would quickly be lost shortly after this time and the slabs would in practice be unloaded.

It is more difficult to say whether the load was kept or not during the test of the loaded cylinders. Both ends, where the bars were located, were insulated but that does not ensure that the temperatures were kept at such low level that it did not affect the load.

Each beam was loaded in two points with an external load. The load was 28 kN at each point. The measured load and the measured deformation of the central point of each beam are shown in figure 21. The load was applied by hydraulic jacks with a constant hydraulic pressure. The load from each actuator was controlled before the fire test. The load value given in figure 21 is a mean value of all actuators used in the test.

The load was applied approximately 60 minutes before the fire test. The mid-span deformation was measured on each beam. The results show that the beam without fibres (LB 40 01) deformed slightly more compared to the beam with fibres (LB 40 11). Beam LB 40 01 had after some time a higher deformation rate which probably was due to spalling.

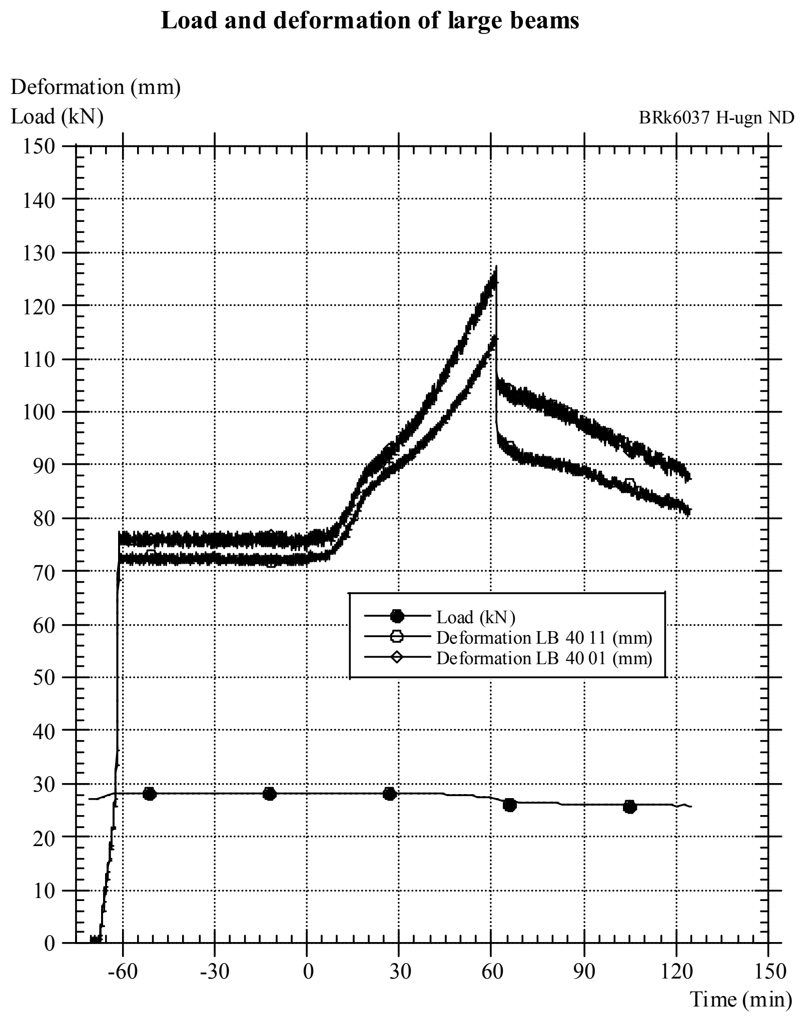

Figure 21. Load and deformation of the large beams during the fire test.

4.1.6 Observations during the test

Table 17 show the general observations made during the fire test. It was not possible to observe all specimens continuously so the table gives approximate times when spalling or other visible phenomena occurred. Photos of the large specimens after the test are presented in Appendix D2.

Table 17. Observations during the fire test.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
-60:00	Load applied on beams
0:00	Start of fire test
6:40	Slab LS 40 01: Starts spalling Slab LS 30 01: Starts spalling
7:20	Cylinders LC 40 03 – LC 40 04: Starts spalling
7:50	Cylinders LC 30 03 – LC 30 04: Starts spalling
8:00	Cylinders LC 30 01 – LC 30 01: Starts spalling
8:50	Beam LB 40 01: Starts spalling
9:00	Cylinders LC 40 01 – LC 40 02: Starts spalling
10:30	Beam LB 40 01: Spalling at the east side, close to the support
11:00	Slab LS 55 01: Starts spalling
11:40	Beam LB 40 01: Spalling at the west side, close to the support
13:50	Beam LB 40 01: Some spalling at the centre, a piece 10 x 20 cm
15:30	Slab 40 01: Reinforcement is exposed Slab 55 01: Reinforcement is exposed
18:00	Slab 30 01: Reinforcement is exposed
23:00	Slabs 30 01, 40 01 and 55 01: Still spalling, but not violently
23:30	Slab 40 11: Fluid (water) bubbling on the surface in the furnace
27:15	Slab 40 01: Fluid (water) dropping from the specimen in the furnace
28:00	Slab 30 01: Fluid (water) dropping from the specimen in the furnace
32:00	Slab 40 01: Light spalling
35:00	No visible spalling
61:00	Test is terminated

4.2 Large furnace tests of tunnel concretes

4.2.1 General information

The fire tests were carried out in a horizontal furnace on June 16 and June 26, 2003. In the first test small specimens were placed on the bottom of the furnace. Since no evaluation of the tests on the small specimens was possible due to melting, these specimens were omitted from the second furnace test. Temperatures in the concrete were measured during the tests and the results are presented in Appendix C.

4.2.2 Temperatures

The furnace was controlled by a specially designed time-temperature curve. The curve was designed to simulate a fire in the trains assumed to be used in the City tunnel in Malmö. The curve was theoretically determined by Ingason (2000). The used time-temperature curve is shown in figure 22. The furnace was heated during 180 minutes after which a cooling phase was used for 120 minutes. Hence the total test time was 300 minutes.

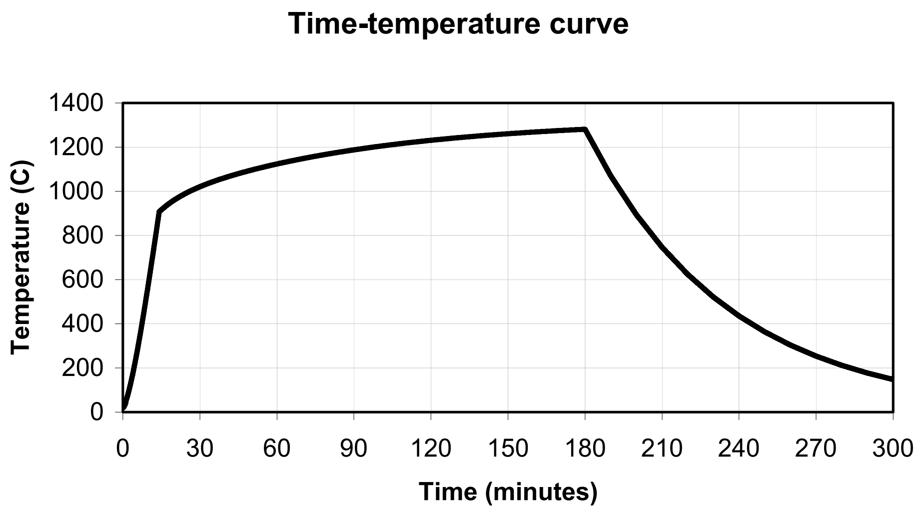

Figure 22. Specially designed time-temperature curve for the City tunnel in Malmö (Ingason, 2000).

The furnace temperature was measured by 17 plate thermometers (T1-T8 and T11-T19) during the first furnace test, and 9 plate thermometers (T11-T19) during the second furnace test. Plate thermometers T1-T8 were placed 500 mm above the floor of the furnace. These plate thermometers were not used for the control of the furnace temperature. Plate thermometers T11-T19 were placed 100 mm below the fire exposed surface of the large slabs at the commencement of the tests. These plate thermometers were used for the control of the furnace temperature. The average temperatures in the furnace (of T11-T19) in relation to the by the sponsor specified time-temperature curve are shown in figures 23 and 25. The measured temperatures of all plate thermometers are presented in figure 24 and 26.

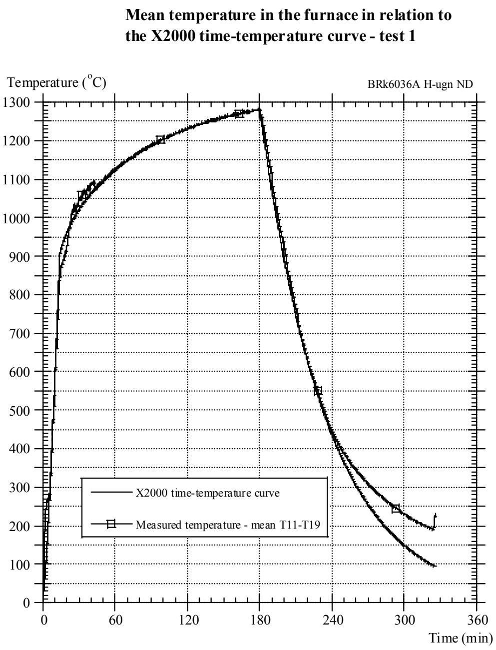

Figure 23. Mean temperature in the furnace.

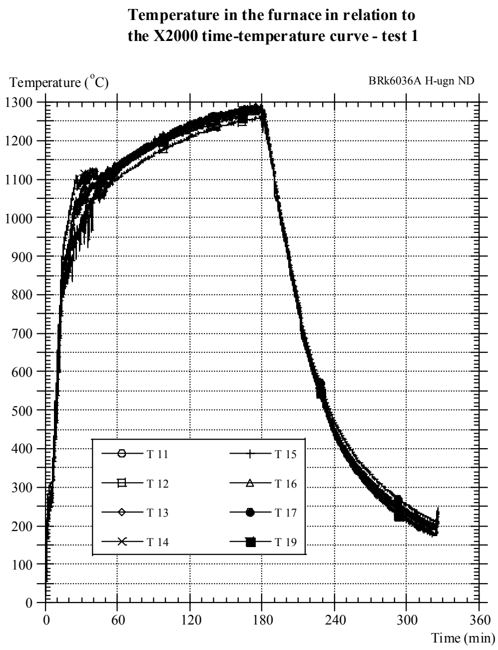

Figure 24. Temperature of each plate thermometer in the furnace.

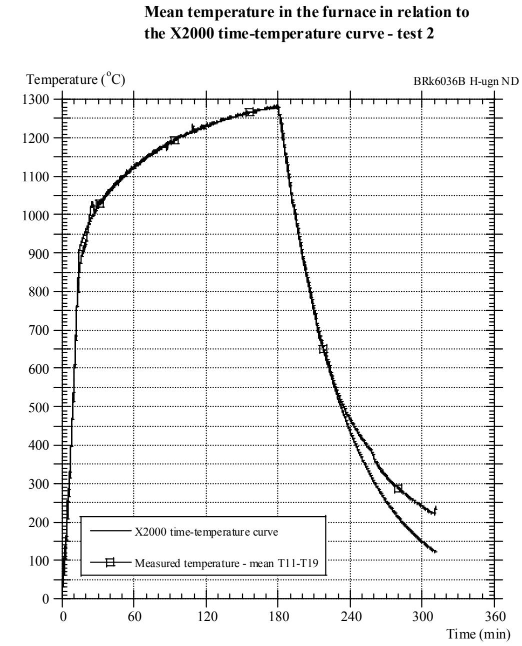

Figure 25. Mean temperature in the furnace.

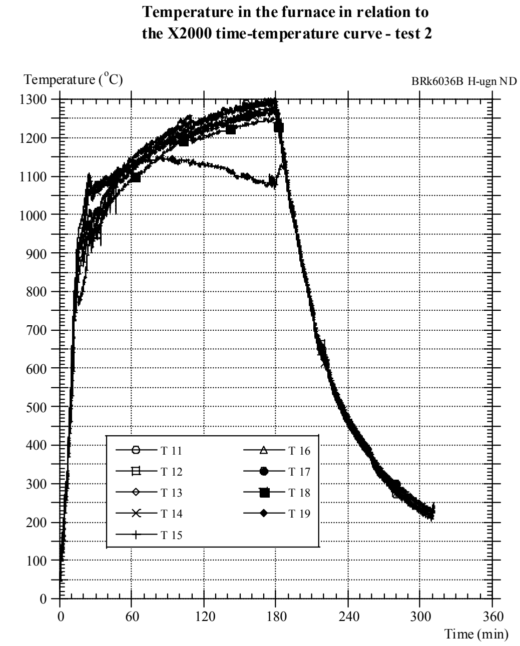

Figure 26. Temperature of each plate thermometer in the furnace.

4.2.3 Pressure

The pressure in the furnace in relation to the ambient pressure in SPs furnace hall was measured 0.3 m below the fire exposed surface of the test specimen.

The furnace was controlled so that an overpressure of approximately 17 Pa was kept at the level of the pressure measurements. This corresponds to 20 Pa overpressure 100 mm below the fire exposed surface of the slabs. The furnace pressure during the first fire test is shown in figure 27, and during the second fire test in figure 28. The reasons for the sudden peaks in the pressure was due to extra cooling of the exhaust gases. The cooling was necessary for the smoke cleaning system used.

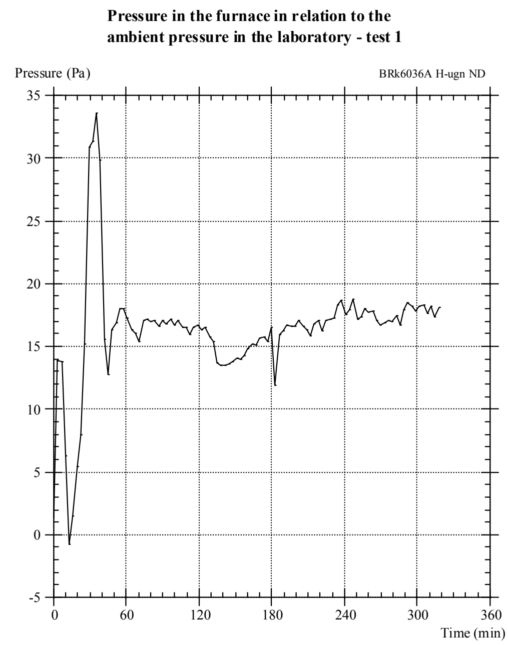

Figure 27. Pressure in furnace, first test.

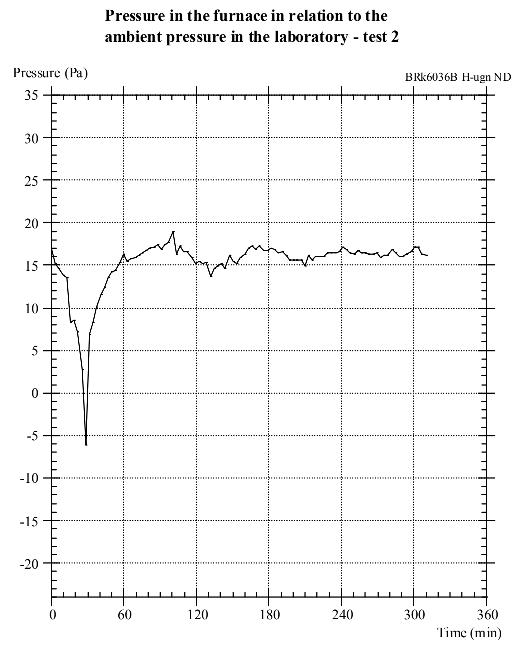

Figure 28. Pressure in furnace, second test.

4.2.4 Spalling

The amount of spalling of the large beams is shown in table 18. It shall be noted that when calculating the weight loss the amount of evaporated water was estimated to 2.8 % which is the amount giving 0 % weight loss for specimen D2.

Table 18. Spalling of the large slabs.

Specimen	Weight loss (%)	Mean spalling (mm)	Maximal spalling (mm)	Characteristic spalling (mm)
A1	21.8	162	314	273
A2	16.9	127	227	213
Mean of A	*19.4*	*144*	*271*	*243*
B1	4.0	23	37	35
B2	1.8	8	38	28
Mean of B	*2.9*	*15*	*38*	*31*
C1	8.3	56	80	85
C2	9.7	61	76	78
Mean of C	*9.0*	*58*	*78*	*81*
D1	0.6	0	32	3
D2	0.0	0	7	2
Mean of D	*0.3*	*0*	*19*	*2*
E1	23.9	182	359	306
E2	12.5	84	130	116
Mean of E	*18.2*	*133*	*245*	*211*
F1	6.7	40	67	56
F2	5.0	33	57	54
Mean of F	*5.9*	*36*	*62*	*55*

4.2.5 Loading

The applied load on the specimens was measured using four load cells. The placement of the load cells are shown in figure 3, paragraph 2.4. Table 19 show the approximate time when the load in the steel bars starts decreasing for each specimen couple. These results indicate a decreasing load after 45-50 minutes for concrete A and E. For concretes B, C, D and F the load starts decreasing after 200 minutes. It should be noted that the measurements on specimen couple B2-C2 are unreliable since the load cell was out of function after the fire test. Results from the load measurements are presented in Appendix A.

Table 19. Time when the load start decreasing.

	Time to decreasing load (minutes)	
	Bar 2	Bar 4
A1 - B1	45	-
A2 - E2	45	-
B2 - C2	180*	-
C1 - D1	200	-
D2 - F2	200	200
E1 - F1	50	45

* Unreliable measurements due to fault in the load cell

4.2.6 Observations

Tables 20 and 21 show the general observations made during the fire test. It was not possible to observe all specimens continuously so the table gives approximate times when spalling or other visible phenomena occurred. Photos of the specimens after the tests are presented in Appendix F2.

Table 20. Observations during the first fire test.

Time min:s	*Observations (the observations refer to the unexposed side if nothing else is stated)*
00:00	Start of test.
10:30	C1, E1: Surface spalling starts
11:00	F1: Surface spalling starts
12:00	A10, C10, A22: Spalling in the corners
14:10	A21, C21: Spalling in the corners
14:20	D1, F1: Surface spalling at some spots
15:40	A1: Large spalling
16:30	C10: Water pouring from the column
17:30	D1: Only two fields, appr. 10 %, have scaled off
19:30	A1, C1, E1: The reinforcement steel is visible
20:20	F1: The reinforcement steel is visible at two spots
21:40	B6, D6, F6, D7, F7 ,B7, B21, D21, F21, B22: No visible spalling
22:25	D1: No spalling since 17:30
22:30	The intensity of the spalling has decreased
23:40	A1, E1: the reinforcement steel is hanging down
24:30	D10: Only one part of the surface, appr. 10 x 10 cm, has spalled
24:45	E1: Reinforcement steel has broken
26:10	A1, C1: Still spalling
26:40	F1: Two 40 cm fields of the reinforcement steels are visible
27:30	E1: Water is boiling at the surface
28:55	E1: Still spalling and water is boiling at the surface at some points
31:00	A1: Water is boiling at the surface
32:00	A10: Lower corner has spalled 30 cm upwards
34:30	Cubes almost completely covered with debris from the slabs
35:30	A1, E1: Still spalling
38:05	E1: Flames from the plastic tubes in which the pre-stressed bars are passing
40:00	Moisture on the unexposed face of specimens A1 and E1
45:00	A1, E1: Still spalling
58:00	E1: Moisture on an area of 2 dm^2 on the unexposed surface
110:00	D10: 10 cm of the lower part has fallen off
151:00	C10: The metal plate on the lower part has fallen off
165:00	A10, C10, D10: the concrete is melting and dripping down
300:00	The test is terminated.

Table 21. Observations during the second fire test.

Time min:s	*Observations (the observations refer to the unexposed side if nothing else is stated)*
00:00	Start of test.
09:30	A11: Discolouration of the surface
10:40	C2: Small 1 cm^2 parts are falling off
10:45	A11: Light spalling of the surface
11:40	A2: Heavy spalling
13:10	B2, D2, F2: No visible spalling A2, E2, C2: Heavy spalling
15:15	E2: Water is boiling on the surface
15:40	A11, C11: Some spalling D11: No visible spalling
17:00	F2: The whole surface is spalling
17:55	B2: A 70 x 70 cm^2 are has scaled off
18:30	A2: The reinforcement bars are visible
19:20	C2, E2: The reinforcement bars are visible
23:50	F2: The reinforcement bars are visible
24:00	C2: Water is boiling on the surface
25:00	The intensity of the spalling decreases
26:30	A2: Water is boiling on the surface
28:25	D11, D2: No visible spalling
38:00	B2: 50% of the surface is undamaged
40:00	No moisture on the unexposed surface of the slabs
46:00	A2: Visible flames from the plastic tubes in the slabs
60:30	A2: Pre-stressed bars are visible
61:00	A2: Unexposed surface is moist in the centre, 40 x 15 cm
82:00	Some melting of concrete and steel
96:00	D11: 5 cm of the lower part has fallen down
100:00	The hanging reinforcement is melting
300:00	The test is terminated.

The fire exposed surface of all large slabs had melted and got a glass-like appearance due to the very high temperatures. For those specimens where the reinforcement steel had been uncovered, some of the reinforcement bars were hanging straight down, see photos in Appendix F.

The columns had melted and got a conical shape. Some of the reinforcement, at the lower part, was uncovered and melted.

During the first fire test, small specimens were placed at the floor of the furnace. These specimens had partly melted, and they were covered with melted debris from the large slabs and columns.

4.3 Small furnace tests

4.3.1 Self-compacting concrete

The amount of spalling of the small slabs of self-compacting concrete is shown in table 22. It shall be noted that when calculating the weight loss, the amount of evaporated water was estimated to 0.5 % which is the amount giving 0 % weight loss for specimen SS 40 13. Temperatures measured in the small slabs as well as observations made during the tests are presented in Appendix B8.

Table 22. Test results small slabs.

Code	w/p	Fibres (kg/m^3)	Stress type	Stress level (MPa)	Fire curve	Mean spalling (mm)	Max spalling (mm)	Charact spalling (mm)	Weight loss (%)
SS3001	0.30	0	Non	0	Std	37	51	50	10.6
SS3002	0.30	0	Non	0	Std	31	52	48	9.5
SS3003	*0.30*	*0*	*External comp*	*2.5*	*Std*	*69*	*94*	*105*	*19.0*
SS3004	0.30	0	External comp	2.5	Std	102	175	186	32.1
SS4001	0.40	0	Non	0	Std	29	45	49	9.1
SS4002	0.40	0	Non	0	Std	26	36	38	7.9
SS4003	0.40	0	External comp	2.5	Std	93	167	170	27.5
SS4004	0.40	0	External comp	2.5	Std	111	180	193	32.5
SS4011	0.40	1	Non	0	Std	0	0	0	0.1
SS4012	0.40	1	Non	0	Std	0	0	0	0.1
SS4013	0.40	1	External comp	2.5	Std	0	0	0	0.0
SS4014	0.40	1	External comp	2.5	Std	0	0	0	0.1
SS5501	0.55	0	Non	0	Std	15	30	30	4.7
SS5502	0.55	0	Non	0	Std	20	34	34	5.2
SS5503	0.55	0	External comp	2.5	Std	76	125	132	26.9
SS5504	0.55	0	External comp	2.5	Std	57	113	117	16.6

Photos of the tested specimens during and after the tests are presented in Appendix E2.

4.3.2 Tunnel concrete

The amount of spalling of the small slabs of tunnel concrete is shown in table 23. It shall be noted that when calculating the weight loss, the amount of evaporated water was estimated to 2.8 % which is the amount giving 0 % weight loss for specimen F23.

Table 23. Test results small slabs.

Code	w/p	Fibres (kg/m^3)	Stress type	Stress level (MPa)	Fire curve	Mean spalling (mm)	Max spalling (mm)	Charact spalling (mm)	Weight loss (%)
A23	0.38	0	External comp	2.5	Std	18	35	10	12.5
B23	0.38	2	External comp	2.5	Std	0	0	0	0.2
C23	0.38	0	External comp	2.5	Std	13	23	9	9.4
D22	0.38	2	External comp	2.5	Std	0	0	0	2.3
D23	0.38	2	External comp	2.5	Std	0	0	0	0.3
E22	0.38	0	External comp	2.5	Std	29	48	9	18.9
E23	0.38	0	External comp	2.5	Std	19	32	12	14.4
F22	0.38	2	External comp	2.5	Std	0	0	0	0.6
F23	0.38	2	External comp	2.5	Std	0	0	0	0.0

4.4 Tests performed at DTU

The results from the tests made on tunnel concretes are presented in Sørensen and Hertz (2003). A summary of the determined spalling is shown in table 24.

Table 24. Summary of spalling measurements made at DTU on tunnel concretes.

Specimen	Amount of spalling	Area of spalling
A20	No spalling	-
B20	No spalling	-
C20	191 gram	95 % of exposed surface
D20	No spalling	-
E20	69.0 gram	80 % of exposed surface
F20	No spalling	-

5 Comparison between different test methods

5.1 Self-compacting concrete

A comparison of spalling between the different specimens and loading conditions can be made in table 25. Generally the small loaded slabs gave the largest amount of spalling and the unloaded cylinders the smallest amount.

Table 25. Spalling of large and small specimens.

Method	Weight loss (%)	Mean spalling (mm)	Maximal spalling (mm)	Characteristic spalling (mm)
Concrete: w/p=0.30				
Large slabs	15.8	45	65	57
Small slabs unloaded	10.0	34	52	49
Small slabs loaded	32.1	102	175	186
Long cylinders unloaded	1.9	-	-	-
Long cylinders loaded	18.6	-	-	-
Concrete: w/p=0.40 without fibres				
Large slabs	18.7	45	67	56
Large beam	3.1	8	40	21
Small slabs unloaded	8.5	28	40	44
Small slabs loaded	30.0	102	174	182
Long cylinders unloaded	3.4	-	-	-
Long cylinders loaded	22.4	-	-	-
Concrete: w/p=0.40 with 1 kg/m^3 fibres				
Large slabs	0.0	0	0	0
Large beam	0.0	0	0	0
Small slabs unloaded	0.1	0	0	0
Small slabs loaded	0.1	0	0	0
Long cylinders unloaded	1.8	-	-	-
Long cylinders loaded	0.2	-	-	-
Concrete: w/p=0.55				
Large slabs	15.3	48	68	62
Small slabs unloaded	5.0	17	32	32
Small slabs loaded	21.7	66	119	124
Long cylinders unloaded	2.8	-	-	-
Long cylinders loaded	17.0	-	-	-

It can be seen from tests on both small slabs and cylinders that the compressive loading has a dramatic effect on the amount spalling. In all cases the specimens loaded in compression spalled much more than the unloaded specimens.

For all concretes, except the concrete including polypropylene fibres which did not spall at all, both weight loss and spalling depth for the large slabs where between the values found for the unloaded and the loaded small slabs. The load level during the test can be an explanation. Since the large slabs lost their concrete covering over the pre-stress wires, they lost the compressive stress after some time. Thus the amount of spalling would be smaller than if the compression had been kept during the complete test.

The small slabs spalled more than the cylinders. This was the case for both unloaded and loaded specimens. A reason for this may be the plastic tube going through the centre of the cylinders where it was possible for water vapour to escape, and thus decrease the vapour pressure within the specimen.

5.2 Tunnel concrete

A comparison of spalling between large and small slabs of tunnel concrete can be made in table 26. In these tests the difference between small and large slabs was not so clear. The tendency is though that the large slabs spalled more than the small slabs. Also here the loading of the large slabs was affected due to the deep spalling. The large slabs were pre-stressed with bars going centrally through the specimens. Hence the spalling should have been larger for the small slabs, but this was not the case. A difference in these tests compared with the tests on self-compacting concrete was the thickness of the specimens. In this series the thickness of the large slabs was 400 mm while the small slabs had a thickness of only 100 mm. Thus the possibility for the water to escape to the unexposed surface is great for the small slabs, which leads to a decreased amount of spalling.

Table 26. Spalling of large and small slabs.

Method	**Weight loss (%)**	**Mean spalling (% of thickness)**	**Maximal spalling (% of thickness)**	**Characteristic spalling (% of thickness)**
Concrete recipe A				
Large slabs	19.4	36	68	61
Small slabs	12.5	18	35	10
Concrete recipe B				
Large slabs	2.9	4	10	8
Small slabs	0.2	0	0	0
Concrete recipe C				
Large slabs	9.0	14	20	20
Small slabs	9.4	13	23	9
Concrete recipe D				
Large slabs	0.3	0	5	1
Small slabs	1.3	0	0	0
Concrete recipe E				
Large slabs	18.2	33	61	53
Small slabs	16.6	24	40	10
Concrete recipe F				
Large slabs	5.9	9	16	14
Small slabs	0.3	0	0	0

In table 27 a comparison is made between spalling tests made with the specially designed spalling equipment at DTU and the full scale tests on slabs with tunnel concrete. The DTU tests showed spalling in only two cases, for concrete C and E. No spalling was observed on concrete A which spalled most in the full scale test. Concrete C spalled most in the DTU tests and spalled least in the full scale tests when looking on the concretes without addition of polypropylene fibres.

Table 27. Comparison between DTU-tests and large slabs.

Concrete	Tests made at DTU		Tests on large slabs	
	Amount of spalling (gram)	Area of spalling (% of surface)	Weight loss (%)	Mean spalling (% of thickness)
A	0	0	19.4	36
B	0	0	2.9	4
C	191	95	9.0	14
D	0	0	0.3	0
E	69	80	18.2	33
F	0	0	5.9	9

Several other specimens with other geometries were tested in the first furnace test of tunnel concretes. All of those small specimens were unloaded during the test. In the observations made during the fire test some spalling could be observed, especially for short columns. Due to the very high temperatures achieved during the test, the specimens melted more or less. Furthermore, the specimens placed on the bottom of the furnace were covered with the debris from the large slabs that spalled. Hence it was not possible to measure any spalling of these small specimens.

6 Conclusions

Full scale and small scale tests have been performed on different qualities of concrete. Self-compacting concrete as well as tunnel concrete have been studied. From these tests the following conclusions can be drawn:

- There is risk for spalling even in the tension zone of beams loaded in bending if the moisture content is high
- The risk and the amount of spalling is greatly reduced if polypropylene fibers are mixed into the concrete
- Specimens loaded in compression spall more than unloaded specimens
- The design of specimens can affect the probability and the amount of spalling
- The results obtained with the DTU test method were not comparable with the full scale tests made in the present study
- Small slabs tested on a small furnace gave a similar spalling as the full scale tests on large slabs given they were loaded during the test
- Small slabs with a smaller thickness than the full scale slabs spalled less than the full scale specimens
- The cylinders used in these tests spalled less than both full scale and small scale slabs

The present study shows that a correctly designed small scale test can give approximately the same risk and the same amount of spalling as a full scale test. It is, however, of great importance that the loading and the boundary conditions are similar. Thus the thickness of the small scale specimen shall be the same as the full scale specimen. The compressive loading shall be kept at the same level in both the full scale and the small scale test during the complete test.

A small in compression loaded slab with the dimensions 600 x 500 x 200 mm^3, and a fire exposed area of 450 x 360 mm^2, gave similar spalling as the full scale tests on slabs with the dimensions 1800 x 1200 x 200 mm^3, where the fire exposed area was 1600 x 1200 mm^2. An advantage with testing small slabs is that they are tested one at the time, and very exact observations on the spalling can be made during the whole test. This is more difficult if several specimens are tested at the same time.

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Appendix A – Load measurements on tunnel concrete

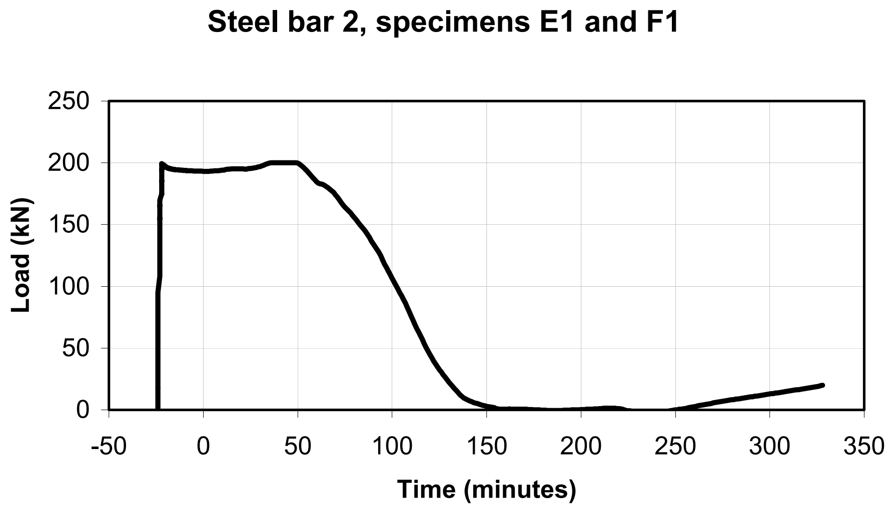

Figure A1. Load in steel bar 2 as a function of time for specimens E1-F1.

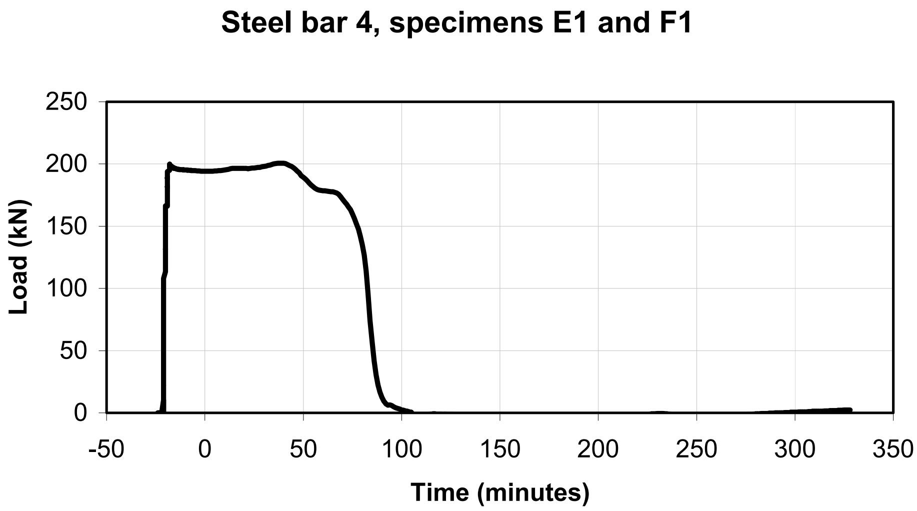

Figure A2. Load in steel bar 4 as a function of time for specimens E1-F1.

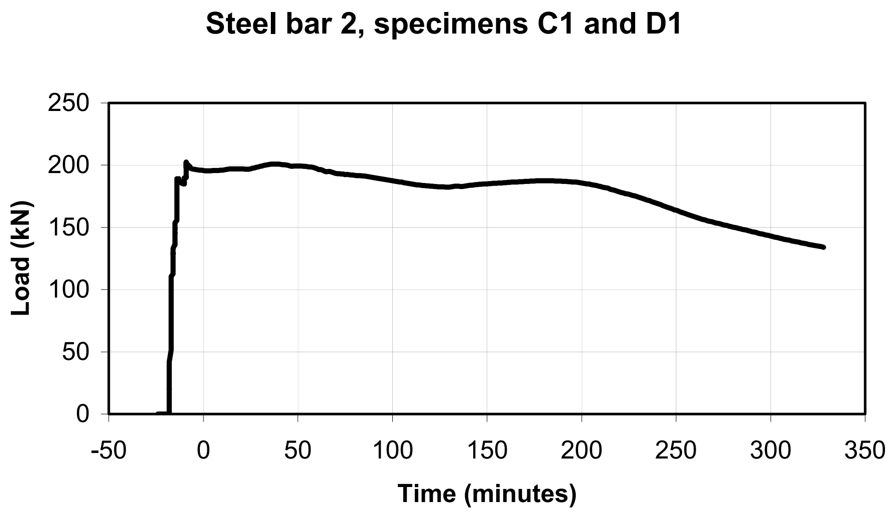

Figure A3. Load in steel bar 2 as a function of time for specimens C1-D1.

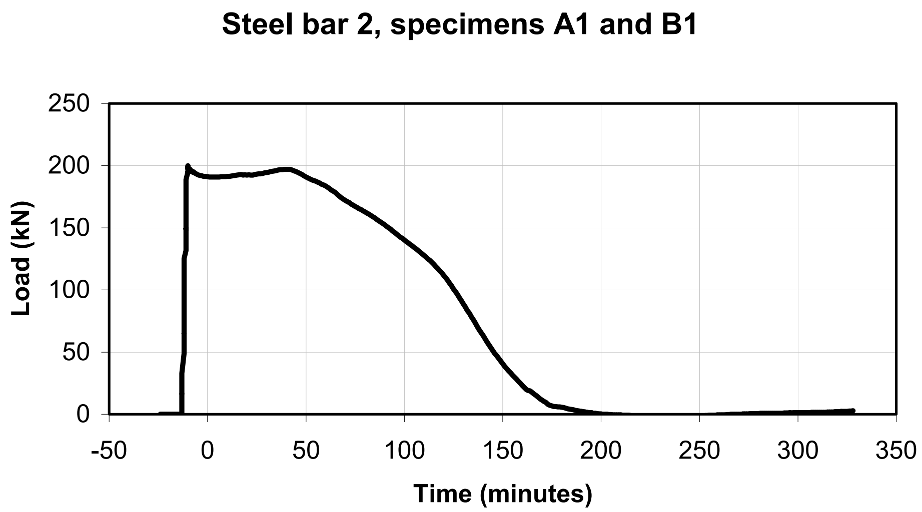

Figure A4. Load in steel bar 2 as a function of time for specimens A1-B1.

Figure A5. Load in steel bar 2 as a function of time for specimens D2-F2.

Figure A6. Load in steel bar 4 as a function of time for specimens D2-F2.

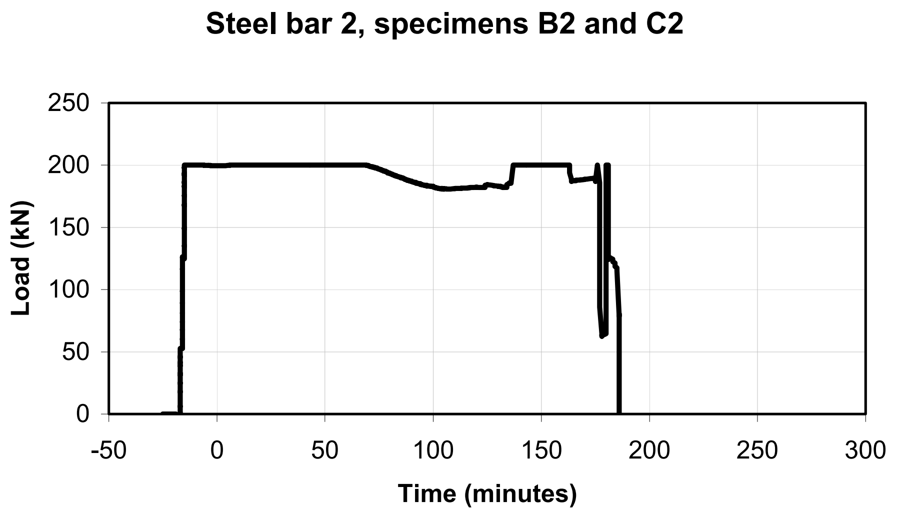

Figure A7. Load in steel bar 2 as a function of time for specimens B2-C2. Unreliable measurements.

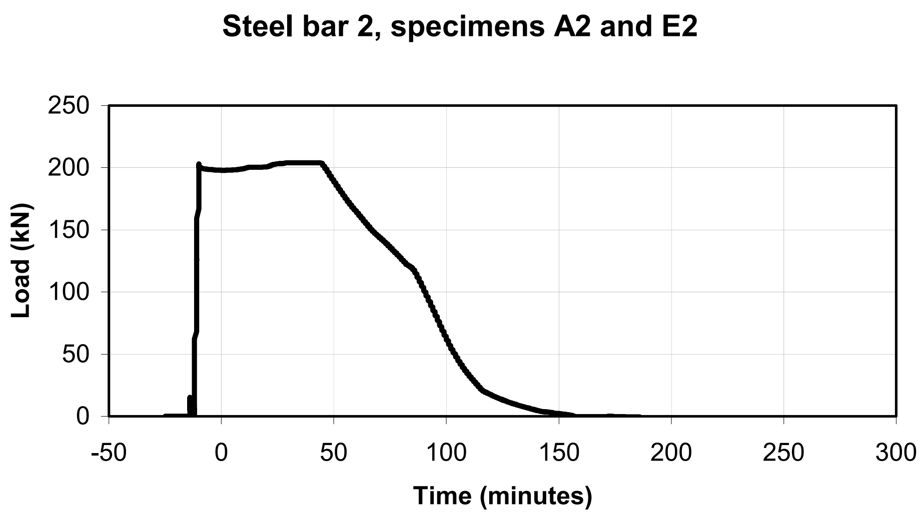

Figure A8. Load in steel bar 2 as a function of time for specimens A2-E2.

Appendix B –Measurements on self-compacting concrete

B1 - Numbering of thermocouples

TC	Place	TC	Place
	Specimen: LS 30 01		***Specimen: LS 40 01***
C1	NW corner – Depth 10 mm	C21	NW corner – Depth 10 mm
C2	NW corner – Depth 25 mm	C22	NW corner – Depth 25 mm
C3	NW corner – Depth 50 mm	C23	NW corner – Depth 50 mm
C4	NW corner – Depth 100 mm	C24	NW corner – Depth 100 mm
C5	NW corner – Unexposed surface	C25	NW corner – Unexposed surface
C6	NE corner – Depth 10 mm	C26	NE corner – Depth 10 mm
C7	NE corner – Depth 25 mm	C27	NE corner – Depth 25 mm
C8	NE corner – Depth 50 mm	C28	NE corner – Depth 50 mm
C9	NE corner – Depth 100 mm	C29	NE corner – Depth 100 mm
C10	NE corner – Unexposed surface	C30	NE corner – Unexposed surface
C11	SW corner – Depth 10 mm	C31	SW corner – Depth 10 mm
C12	SW corner – Depth 25 mm	C32	SW corner – Depth 25 mm
C13	SW corner – Depth 50 mm	C33	SW corner – Depth 50 mm
C14	SW corner – Depth 100 mm	C34	SW corner – Depth 100 mm
C15	SW corner – Unexposed surface	C35	SW corner – Unexposed surface
C16	SE corner – Depth 10 mm	C36	SE corner – Depth 10 mm
C17	SE corner – Depth 25 mm	C37	SE corner – Depth 25 mm
C18	SE corner – Depth 50 mm	C38	SE corner – Depth 50 mm
C19	SE corner – Depth 100 mm	C39	SE corner – Depth 100 mm
C20	SE corner – Unexposed surface	C40	SE corner – Unexposed surface
	Specimen: LS 40 11		***Specimen: LS 55 01***
C41	NW corner – Depth 10 mm	C61	NW corner – Depth 10 mm
C42	NW corner – Depth 25 mm	C62	NW corner – Depth 25 mm
C43	NW corner – Depth 50 mm	C63	NW corner – Depth 50 mm
C44	NW corner – Depth 100 mm	C64	NW corner – Depth 100 mm
C45	NW corner – Unexposed surface	C65	NW corner – Unexposed surface
C46	NE corner – Depth 10 mm	C66	NE corner – Depth 10 mm
C47	NE corner – Depth 25 mm	C67	NE corner – Depth 25 mm
C48	NE corner – Depth 50 mm	C68	NE corner – Depth 50 mm
C49	NE corner – Depth 100 mm	C69	NE corner – Depth 100 mm
C50	NE corner – Unexposed surface	C70	NE corner – Unexposed surface
C51	SW corner – Depth 10 mm	C71	SW corner – Depth 10 mm
C52	SW corner – Depth 25 mm	C72	SW corner – Depth 25 mm
C53	SW corner – Depth 50 mm	C73	SW corner – Depth 50 mm
C54	SW corner – Depth 100 mm	C74	SW corner – Depth 100 mm
C55	SW corner – Unexposed surface	C75	SW corner – Unexposed surface
C56	SE corner – Depth 10 mm	C76	SE corner – Depth 10 mm
C57	SE corner – Depth 25 mm	C77	SE corner – Depth 25 mm
C58	SE corner – Depth 50 mm	C78	SE corner – Depth 50 mm
C59	SE corner – Depth 100 mm	C79	SE corner – Depth 100 mm
C60	SE corner – Unexposed surface	C80	SE corner – Unexposed surface

Specimen: LB 40 01		*Specimen: LB 40 11*	
C81	W side – Depth 25 mm – From edge 300 mm	C102	W side – Depth 25 mm – From edge 300 mm
C82	W side – Depth 50 mm – From edge 300 mm	C103	W side – Depth 50 mm – From edge 300 mm
C83	W side – Depth 100 mm – From edge 300 mm	C104	W side – Depth 100 mm – From edge 300 mm
C84	W side – Depth 100 mm – From edge 25 mm	C105	W side – Depth 100 mm – From edge 25 mm
C85	W side – Depth 100 mm – From edge 50 mm	C106	W side – Depth 100 mm – From edge 50 mm
C86	W side – Depth 100 mm – From edge 100 mm	C107	W side – Depth 100 mm – From edge 100 mm
C87	W side – Unexposed surface – Centric	C108	W side – Unexposed surface – Centric
C88	Centre – Depth 25 mm – From edge 300 mm	C109	Centre – Depth 25 mm – From edge 300 mm
C89	Centre – Depth 50 mm – From edge 300 mm	C110	Centre – Depth 50 mm – From edge 300 mm
C90	Centre – Depth 100 mm – From edge 300 mm	C111	Centre – Depth 100 mm – From edge 300 mm
C91	Centre – Depth 100 mm – From edge 25 mm	C112	Centre – Depth 100 mm – From edge 25 mm
C92	Centre – Depth 100 mm – From edge 50 mm	C113	Centre – Depth 100 mm – From edge 50 mm
C93	Centre – Depth 100 mm – From edge 100 mm	C114	Centre – Depth 100 mm – From edge 100 mm
C94	Centre – Unexposed surface – Centric	C115	Centre – Unexposed surface – Centric
C95	E side – Depth 25 mm – From edge 300 mm	C116	E side – Depth 25 mm – From edge 300 mm
C96	E side – Depth 50 mm – From edge 300 mm	C117	E side – Depth 50 mm – From edge 300 mm
C97	E side – Depth 100 mm – From edge 300 mm	C118	E side – Depth 100 mm – From edge 300 mm
C98	E side – Depth 100 mm – From edge 25 mm	C119	E side – Depth 100 mm – From edge 25 mm
C99	E side – Depth 100 mm – From edge 50 mm	C120	E side – Depth 100 mm – From edge 50 mm
C100	E side – Depth 100 mm – From edge 100 mm	C121	E side – Depth 100 mm – From edge 100 mm
C101	E side – Unexposed surface – Centric	C122	E side – Unexposed surface – Centric

B2 - Measurements on specimen LS 30 01

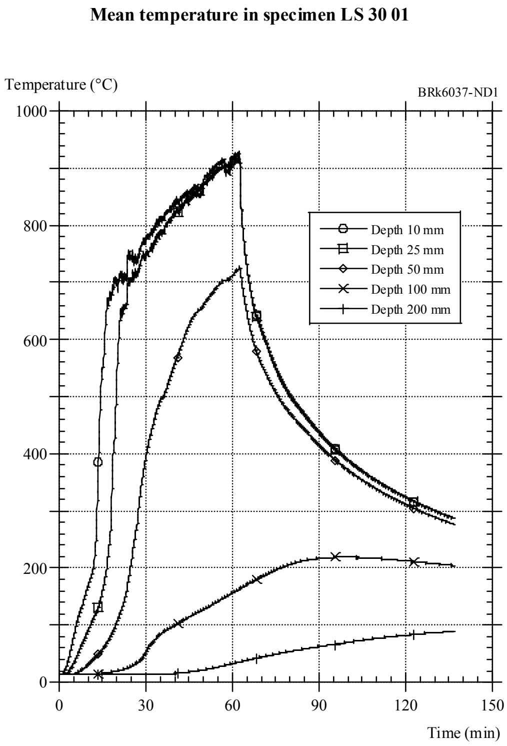

Figure B1. Mean temperature.

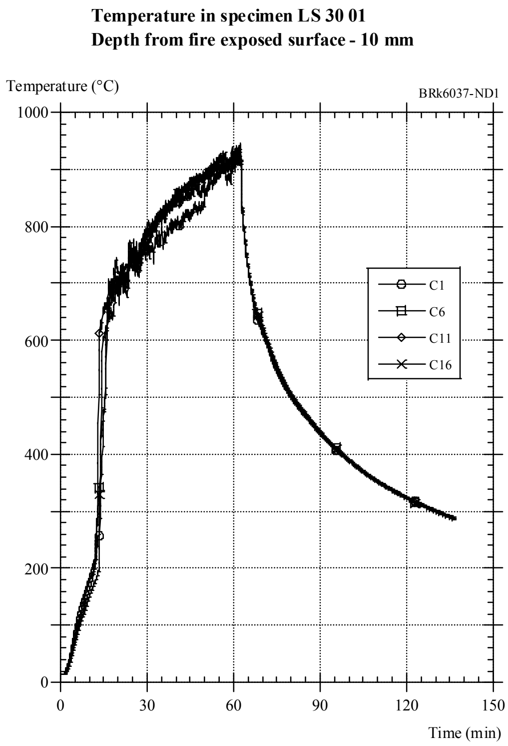

Figure B2. Temperature 10 mm from the exposed surface

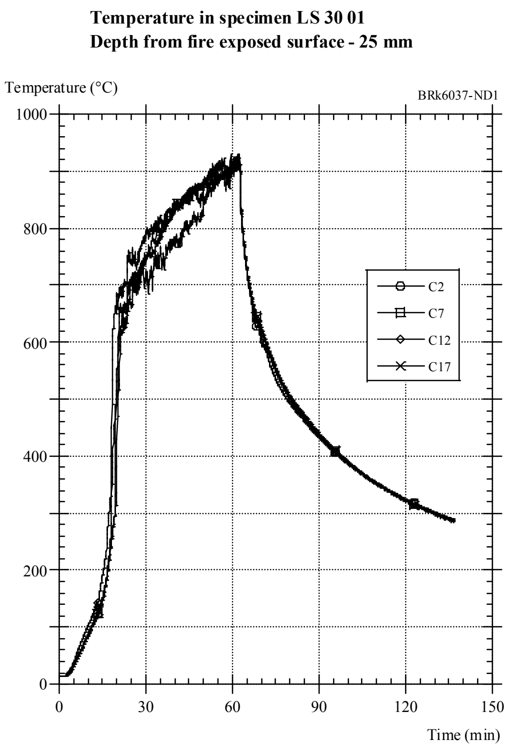

Figure B3. Temperature 25 mm from the exposed surface

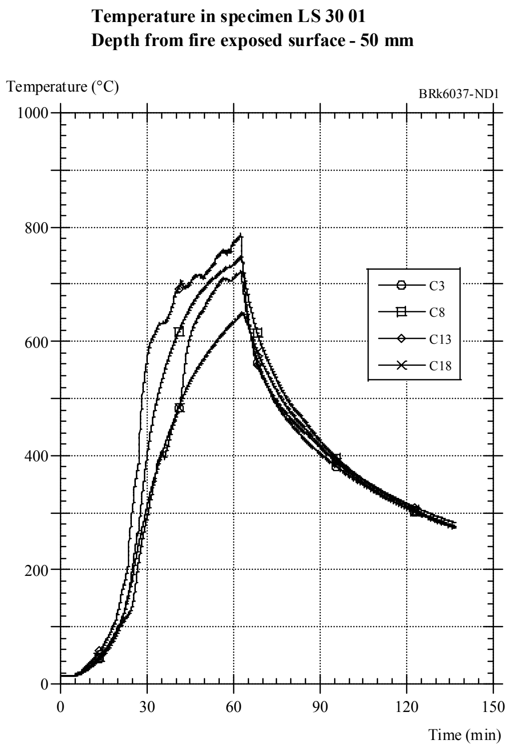

Figure B4. Temperature 50 mm from the exposed surface

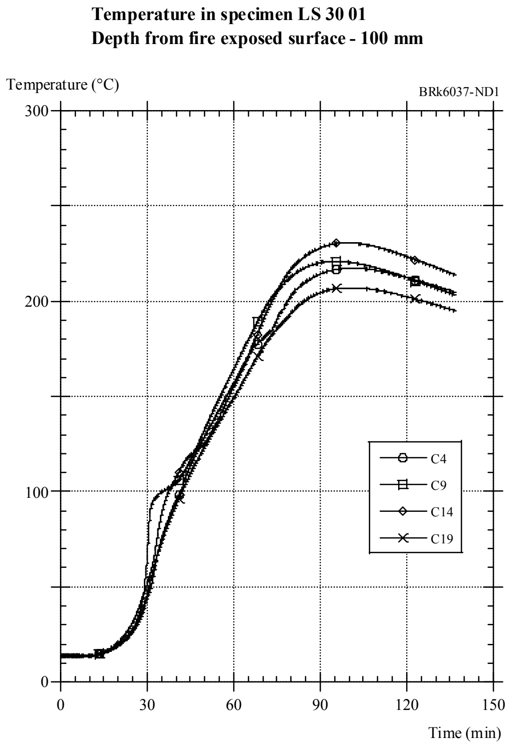

Figure B5. Temperature 100 mm from the exposed surface

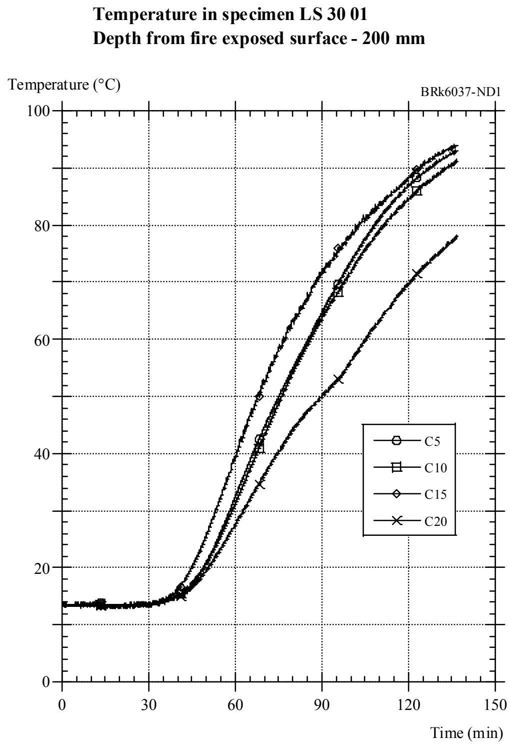

Figure B6. Temperature on the unexposed surface

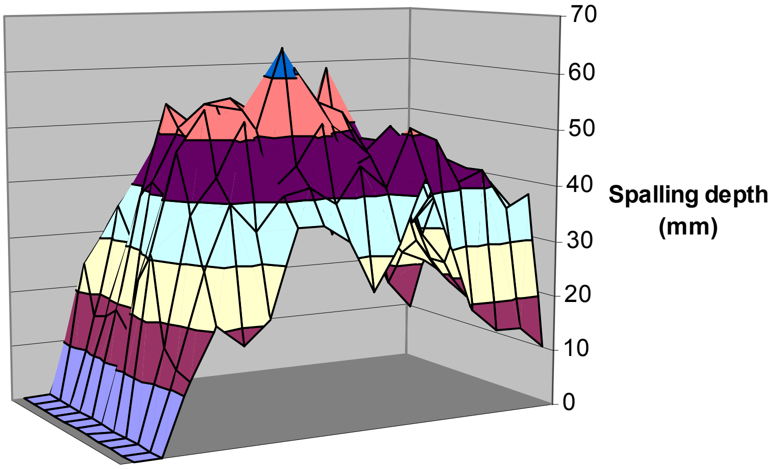

Figure B7. Spalling depth on specimen LS 30 01.

Table B1. Spalling depth of specimen LS 30 01. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	0	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0	0
300	12	13	16	31	26	16	19	17	16	25	12
400	21	29	38	48	40	42	39	31	36	32	24
500	17	40	44	55	49	51	55	47	42	36	31
600	21	35	53	49	55	55	51	45	43	46	41
700	36	41	41	51	54	56	48	43	50	44	40
800	36	42	45	65	57	53	42	48	44	50	42
900	33	39	52	41	61	44	36	46	42	48	33
1000	24	45	44	51	55	39	48	50	42	46	31
1100	32	41	46	48	53	42	41	42	39	40	38
1200	43	51	32	42	46	36	45	60	51	32	31
1300	31	49	48	48	50	47	47	44	42	34	36
1400	19	41	45	37	32	43	42	36	41	34	26
1500	15	43	43	40	37	29	35	41	28	33	34
1600	15	36	40	35	31	23	23	26	23	16	21
1700	11	38	35	37	31	16	18	20	21	11	18

B3 - Measurements on specimen LS 40 01

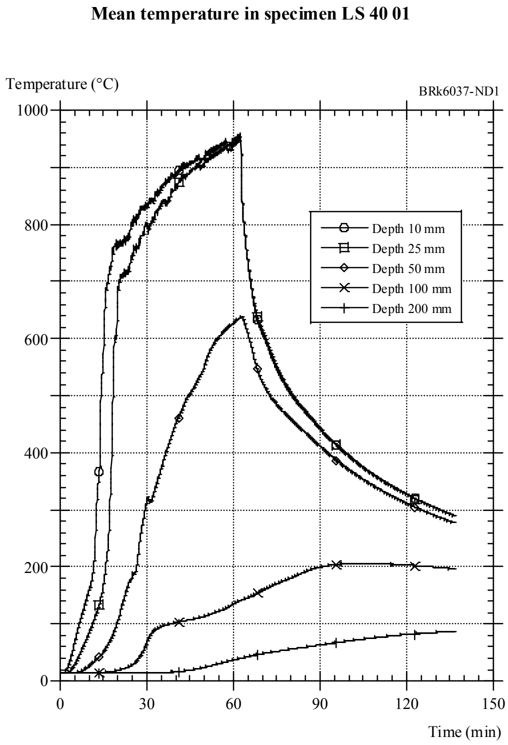

Figure B8. Mean temperature.

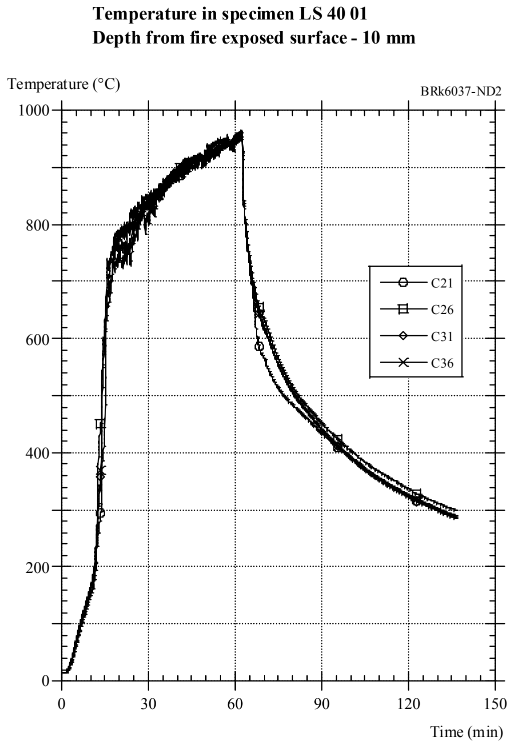

Figure B9. Temperature 10 mm from the exposed surface

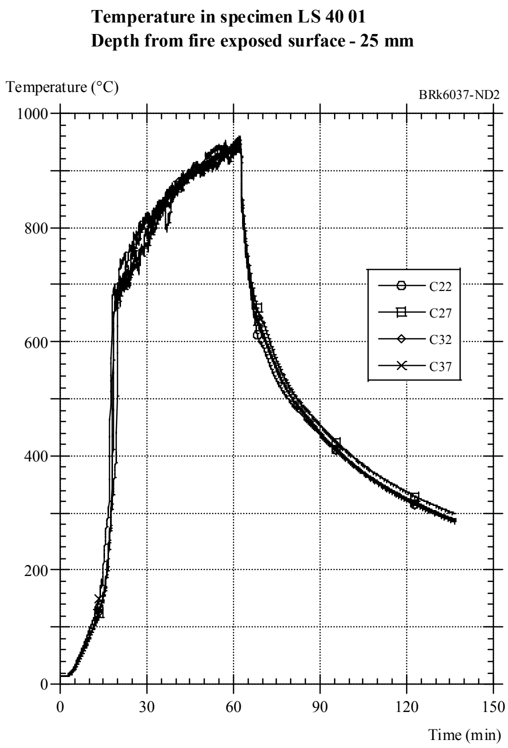

Figure B10. Temperature 25 mm from the exposed surface

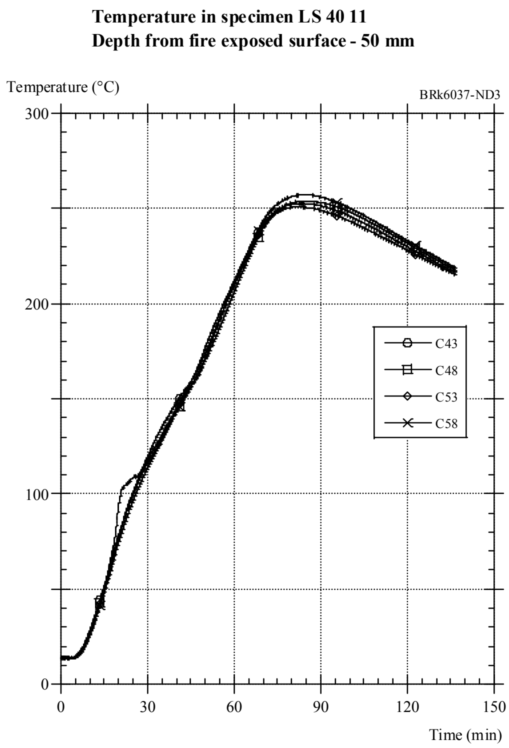

Figure B11. Temperature 50 mm from the exposed surface

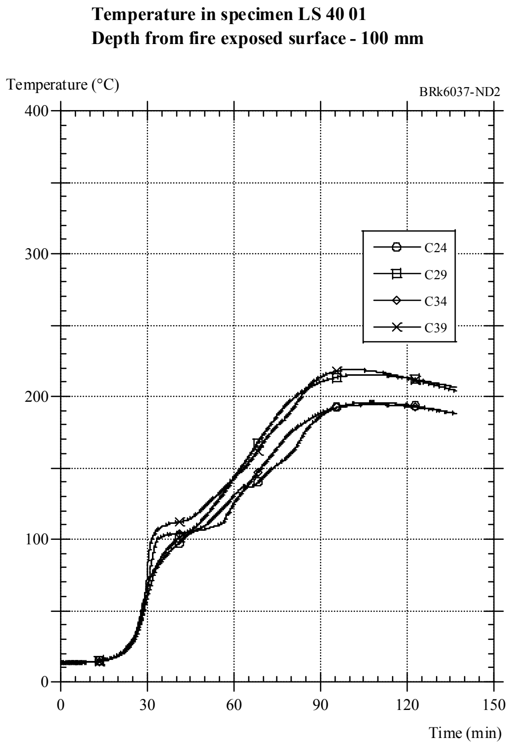

Figure B12. Temperature 100 mm from the exposed surface

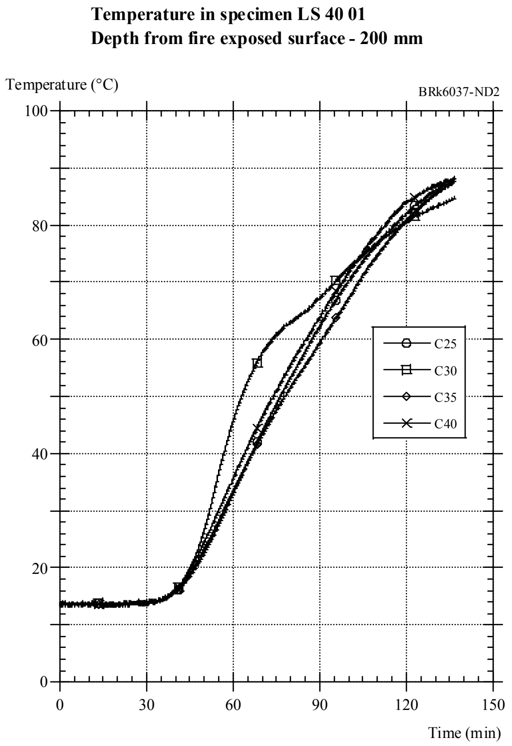

Figure B13. Temperature on the unexposed surface

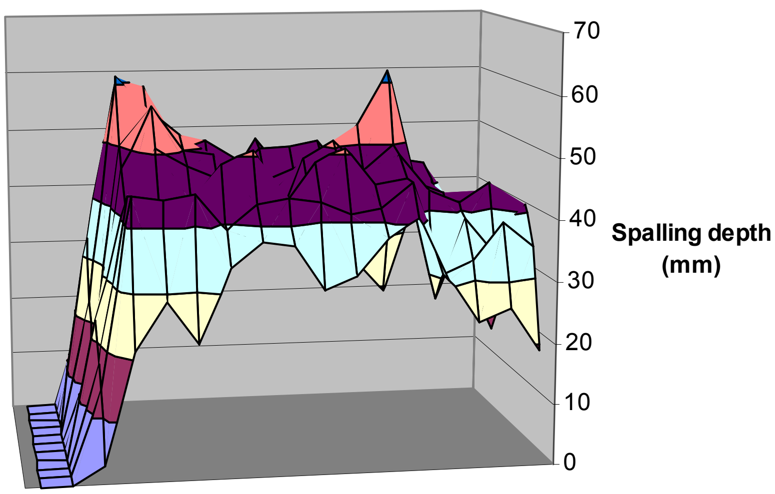

Figure B14. Spalling depth of specimen LS 40 01.

Table B2. Spalling depth of specimen LS 40 01. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	0	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0	0
300	3	14	17	23	16	14	23	33	26	19	16
400	21	45	44	42	47	50	61	58	41	36	23
500	29	44	42	51	57	56	54	59	36	32	31
600	22	45	43	48	50	52	50	45	39	39	28
700	34	39	49	46	49	45	50	42	41	38	31
800	38	43	51	41	33	40	47	43	41	37	34
900	37	44	42	38	36	41	43	48	49	36	31
1000	30	43	49	43	48	46	45	48	43	37	33
1100	32	41	51	48	51	47	46	49	48	45	29
1200	38	42	45	37	46	53	46	43	41	37	33
1300	41	46	46	49	50	62	48	38	44	32	25
1400	31	31	26	43	39	43	45	41	45	35	19
1500	24	33	39	41	37	41	38	42	44	38	34
1600	26	39	33	44	42	31	27	31	31	38	34
1700	19	35	41	38	32	21	16	21	21	25	33

B4 - Measurements on specimen LS 40 11

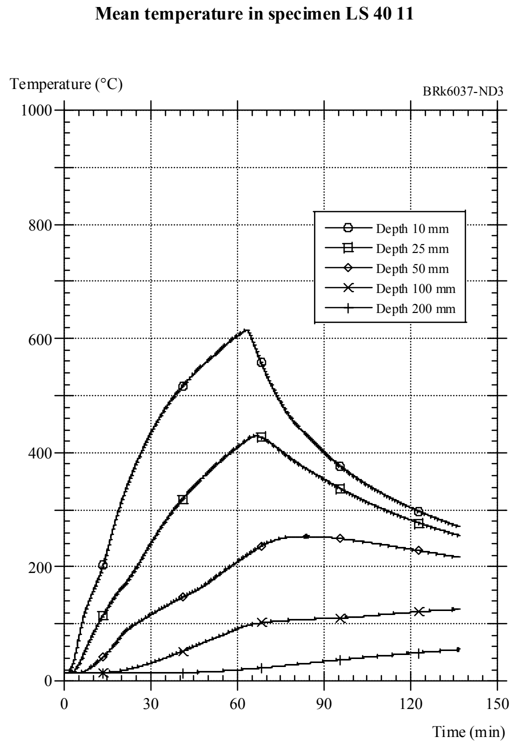

Figure B15. Mean temperature.

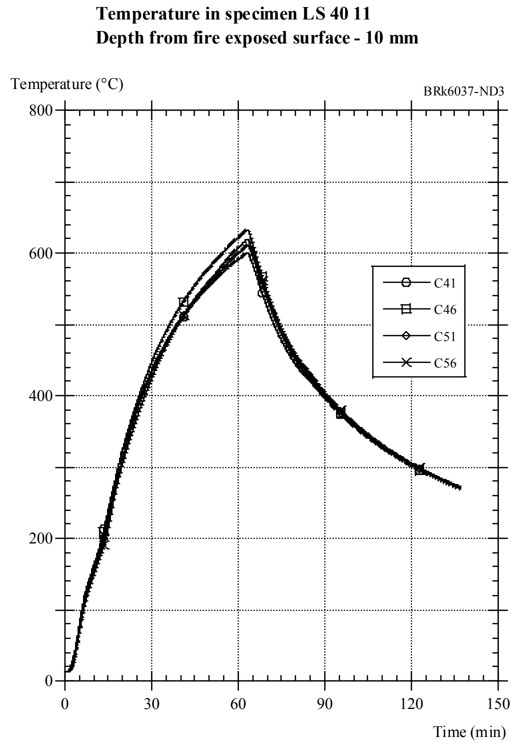

Figure B16. Temperature 10 mm from the exposed surface

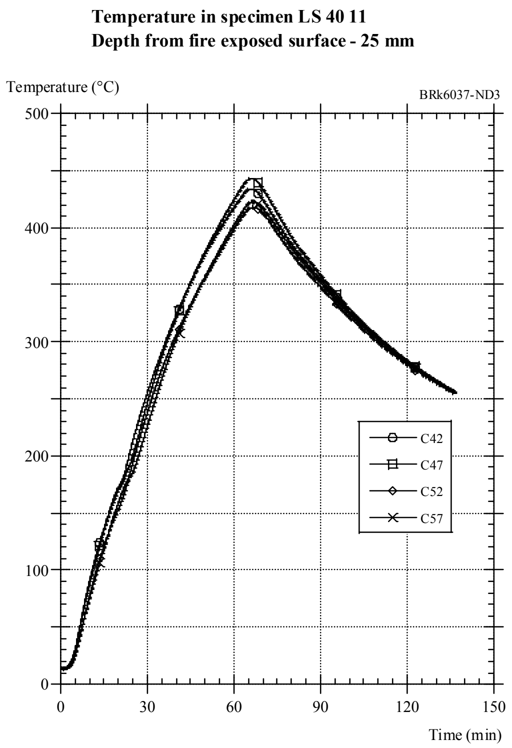

Figure B17. Temperature 25 mm from the exposed surface

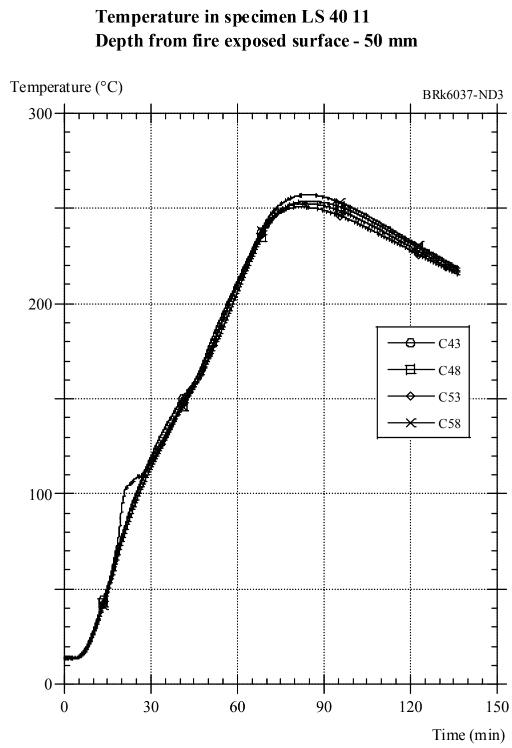

Figure B18. Temperature 50 mm from the exposed surface

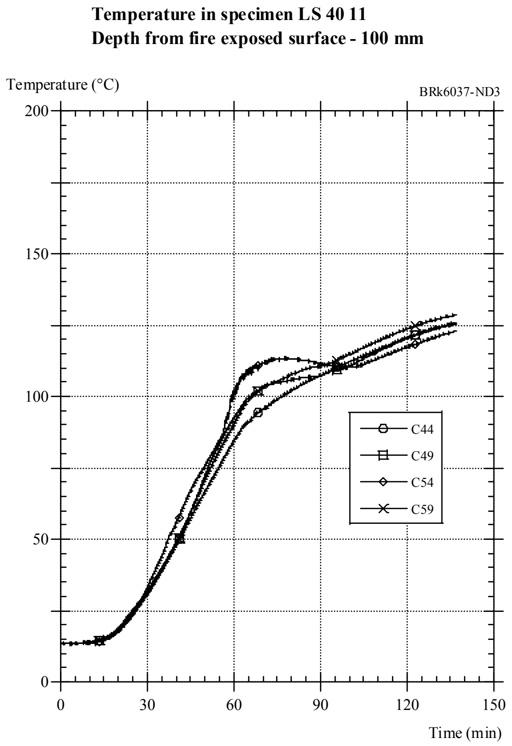

Figure B19. Temperature 100 mm from the exposed surface

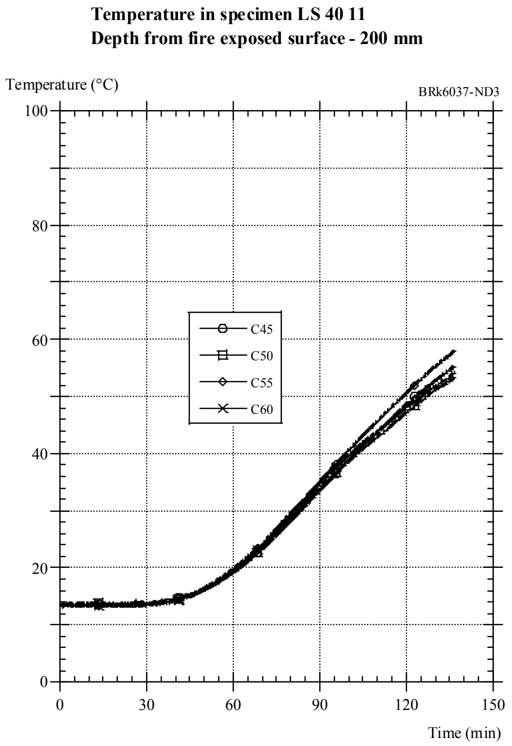

Figure B20. Temperature on the unexposed surface

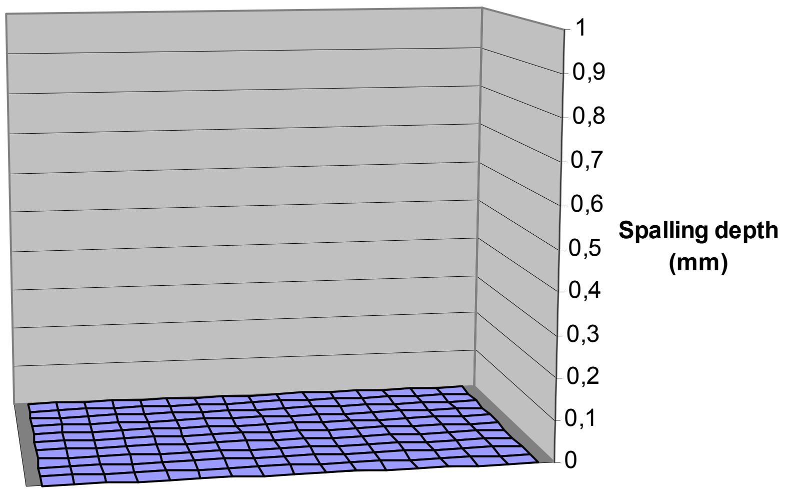

Figure B21. Spalling depth of specimen LS 40 11.

Table B3. Spalling depth of specimen LS 40 11. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	0	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0	0	0	0	0
600	0	0	0	0	0	0	0	0	0	0	0
700	0	0	0	0	0	0	0	0	0	0	0
800	0	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0	0	0	0	0
1100	0	0	0	0	0	0	0	0	0	0	0
1200	0	0	0	0	0	0	0	0	0	0	0
1300	0	0	0	0	0	0	0	0	0	0	0
1400	0	0	0	0	0	0	0	0	0	0	0
1500	0	0	0	0	0	0	0	0	0	0	0
1600	0	0	0	0	0	0	0	0	0	0	0
1700	0	0	0	0	0	0	0	0	0	0	0

B5 - Measurements on specimen LS 55 01

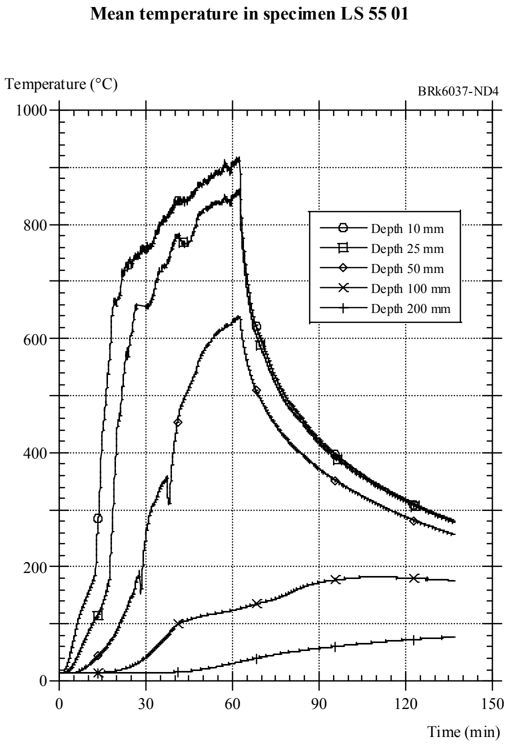

Figure B22. Mean temperature.

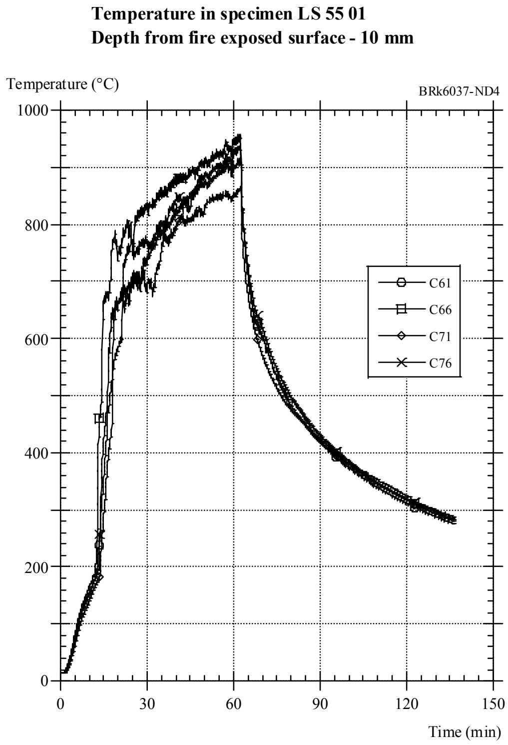

Figure B23. Temperature 10 mm from the exposed surface

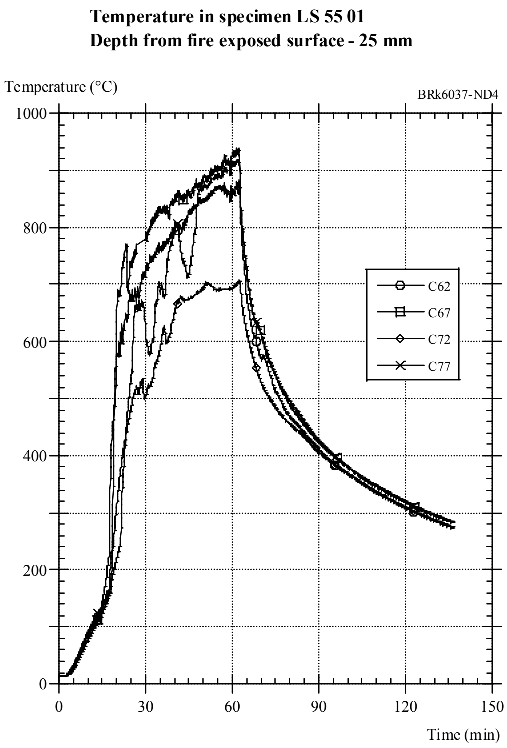

Figure B24. Temperature 25 mm from the exposed surface

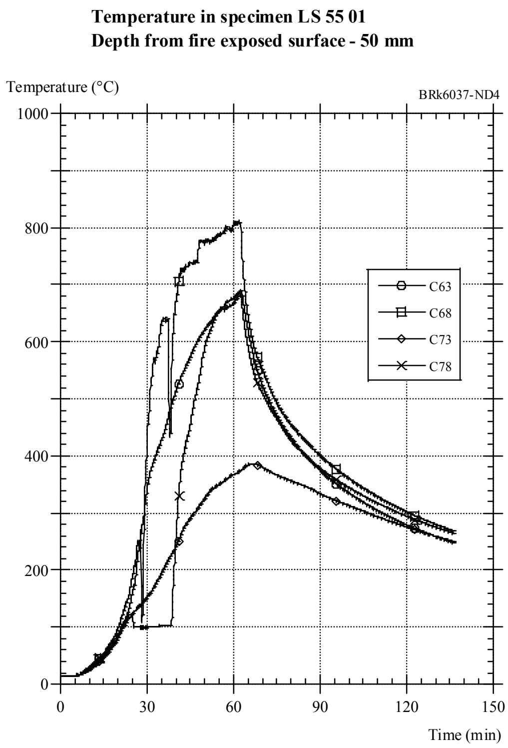

Figure B25. Temperature 50 mm from the exposed surface

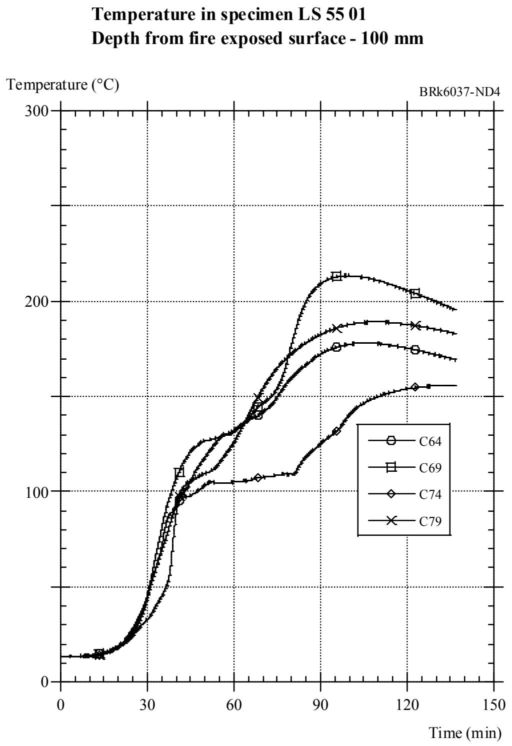

Figure B26. Temperature 100 mm from the exposed surface

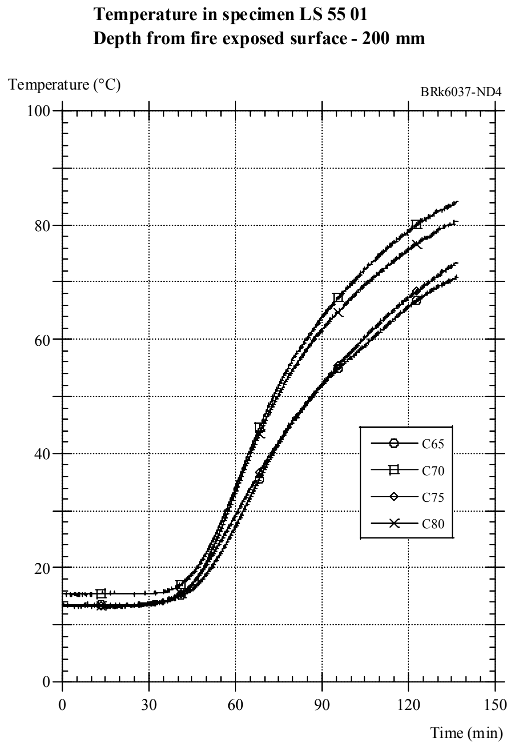

Figure B27. Temperature on the unexposed surface

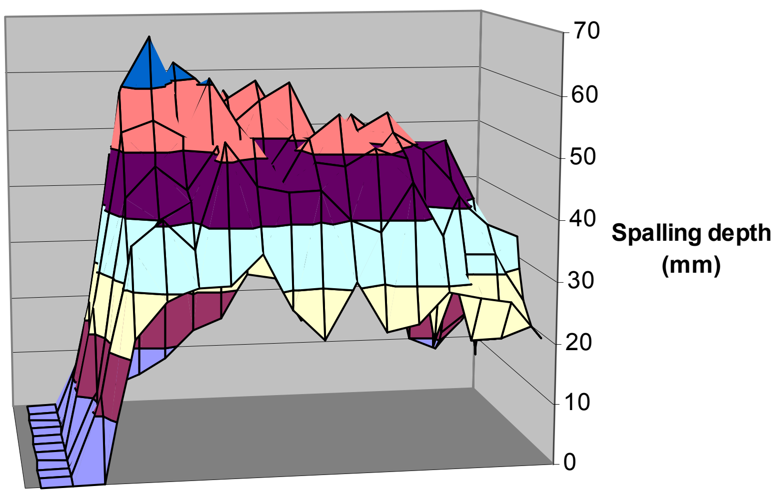

Figure B28. Spalling depth of specimen LS 40 11.

Table B4. Spalling depth of specimen LS 55 01. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	0	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0	0
300	0	13	8	11	24	6	23	13	6	12	0
400	23	37	31	43	53	59	35	40	28	46	3
500	29	41	40	48	55	68	56	53	23	42	5
600	31	36	43	44	52	49	58	63	51	50	8
700	31	53	48	51	49	61	51	59	52	41	13
800	36	46	53	49	45	53	47	52	56	57	15
900	27	45	38	44	47	46	44	56	59	50	23
1000	22	45	49	52	45	47	51	59	51	40	22
1100	31	40	48	56	50	49	44	49	49	32	14
1200	23	38	51	48	46	52	54	46	51	34	16
1300	24	46	49	51	52	55	50	39	46	37	23
1400	29	37	18	28	49	48	49	45	47	46	32
1500	28	20	33	42	44	50	49	47	46	37	10
1600	27	20	33	37	34	40	35	37	44	12	8
1700	21	22	25	35	31	16	17	20	9	16	13

B6 – Measurements on specimen LB 40 01

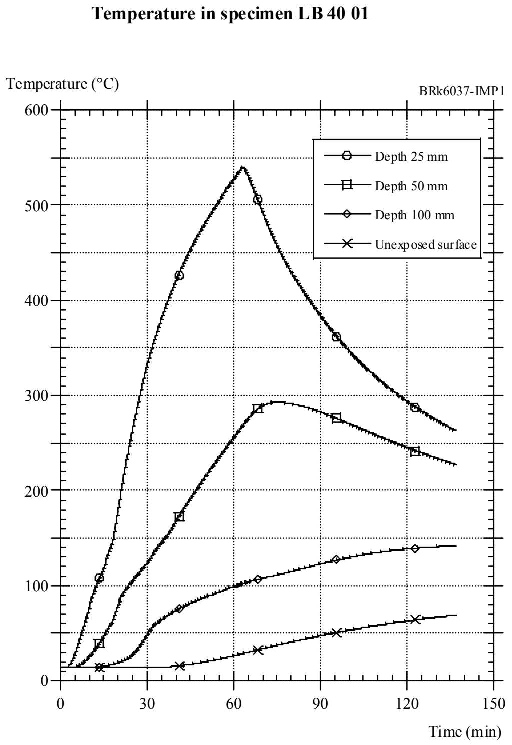

Figure B29. Mean temperature at different depths.

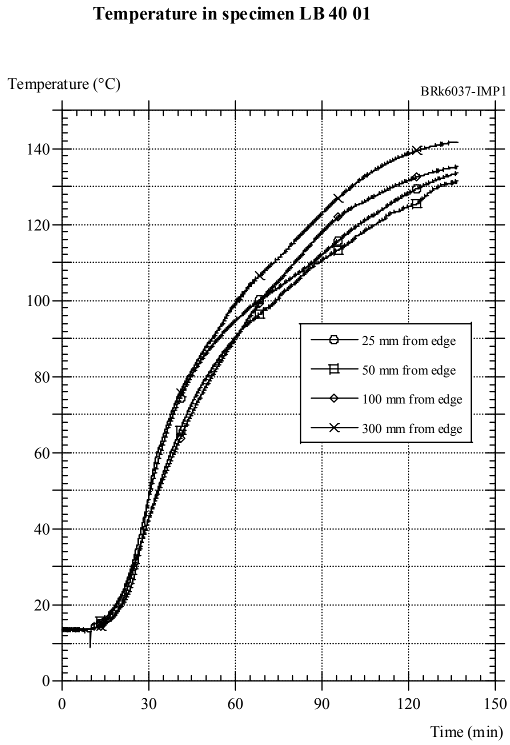

Figure B30. Mean temperature at different positions from the edge

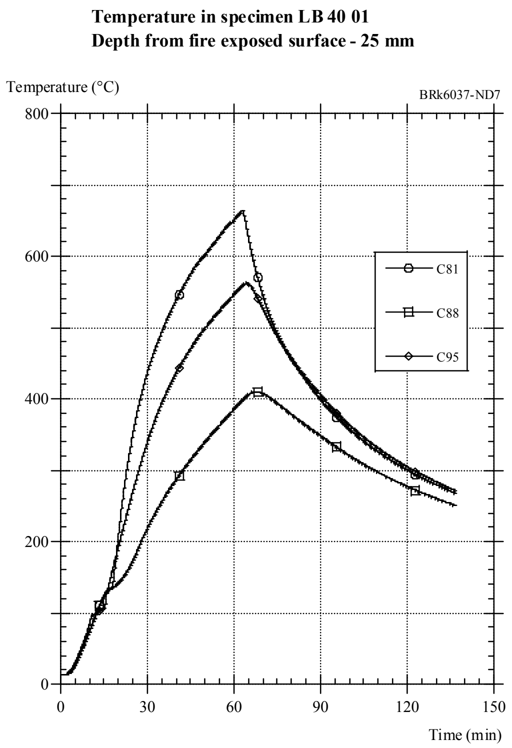

Figure B31. Temperature 25 mm from the exposed surface

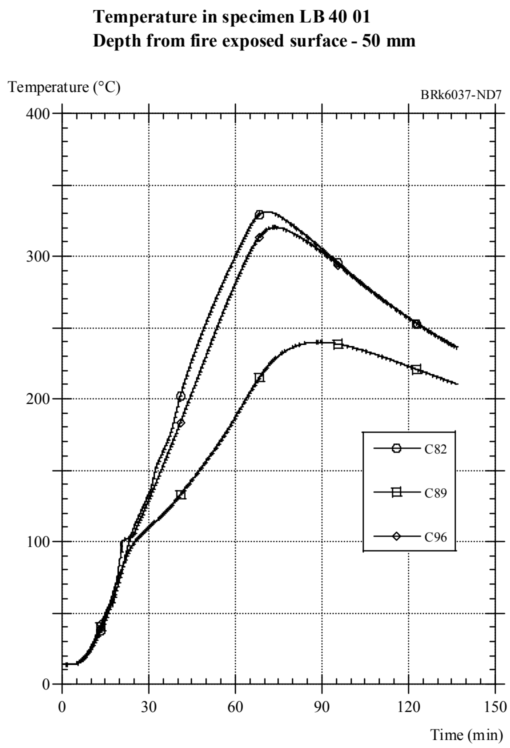

Figure B32. Temperature 50 mm from the exposed surface

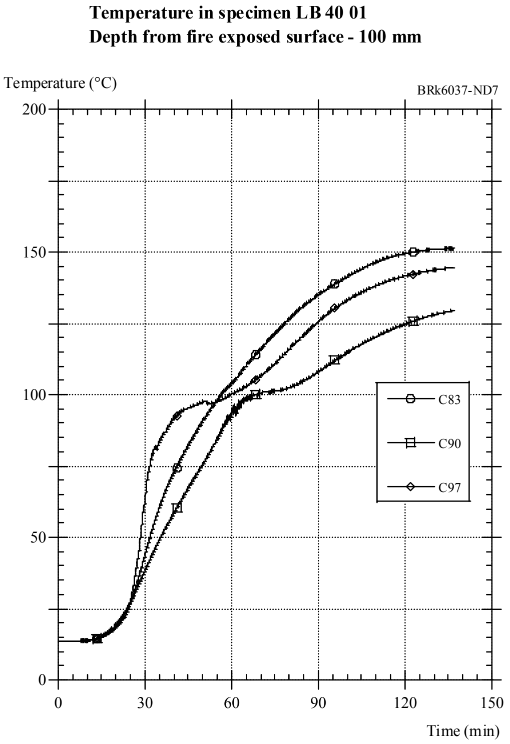

Figure B33. Temperature 100 mm from the exposed surface

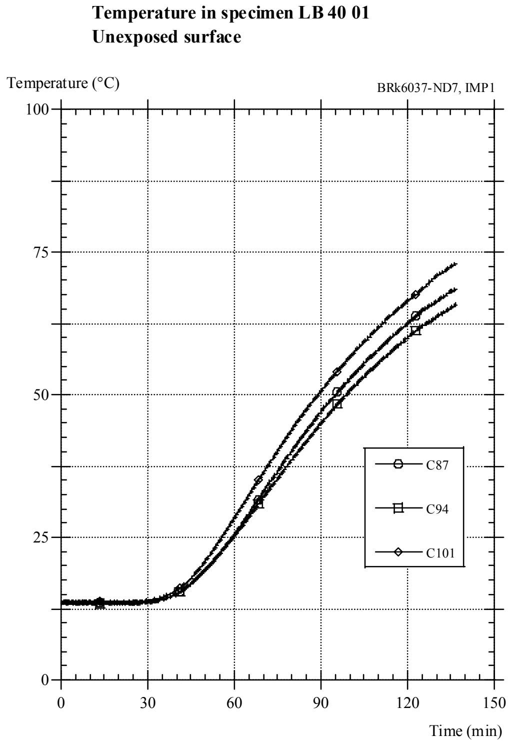

Figure B34. Temperature on the unexposed surface

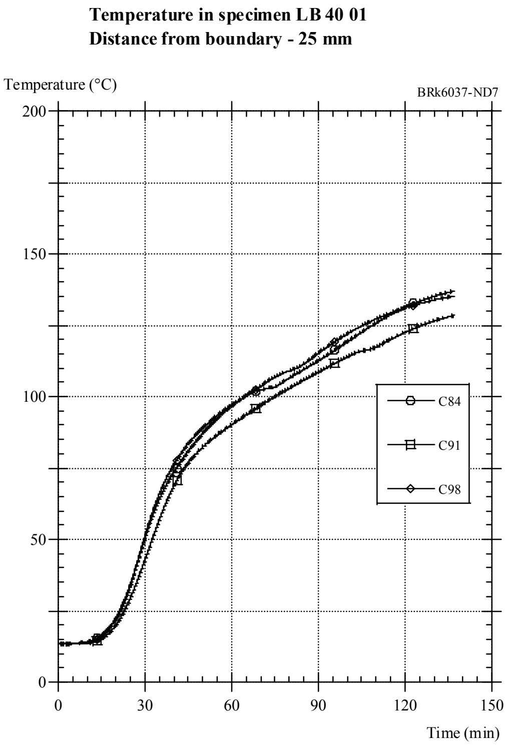

Figure B35. Temperature 25 mm from the edge at 100 mm depth

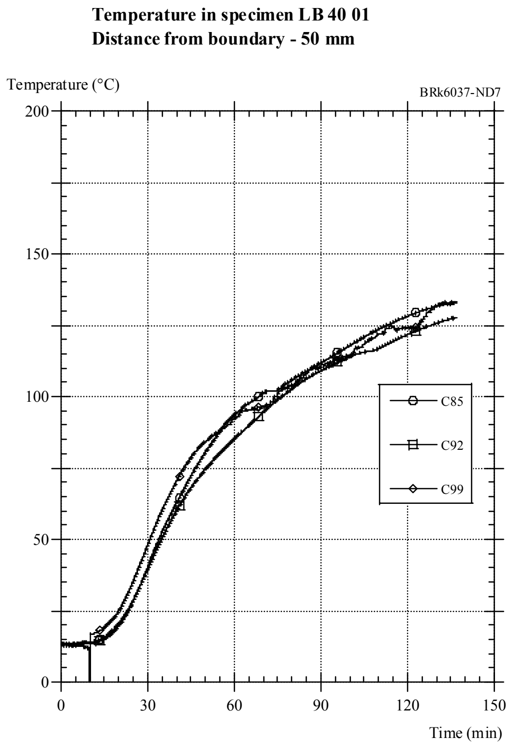

Figure B36. Temperature 50 mm from the edge at 100 mm depth

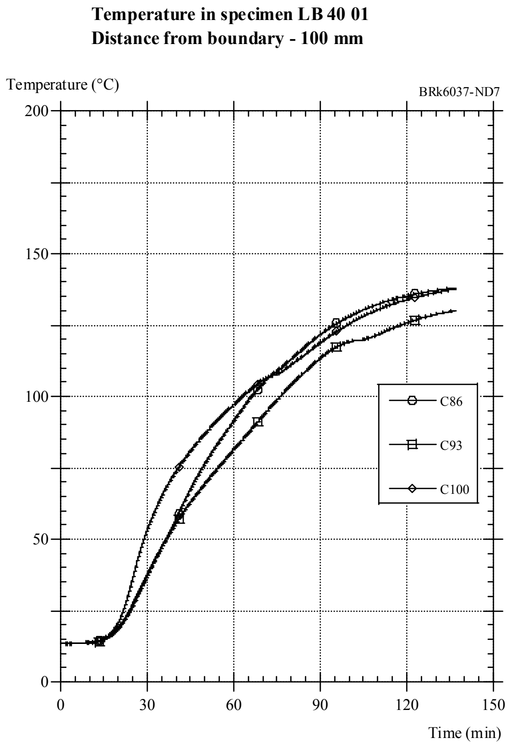

Figure B37. Temperature 100 mm from the edge at 100 mm depth

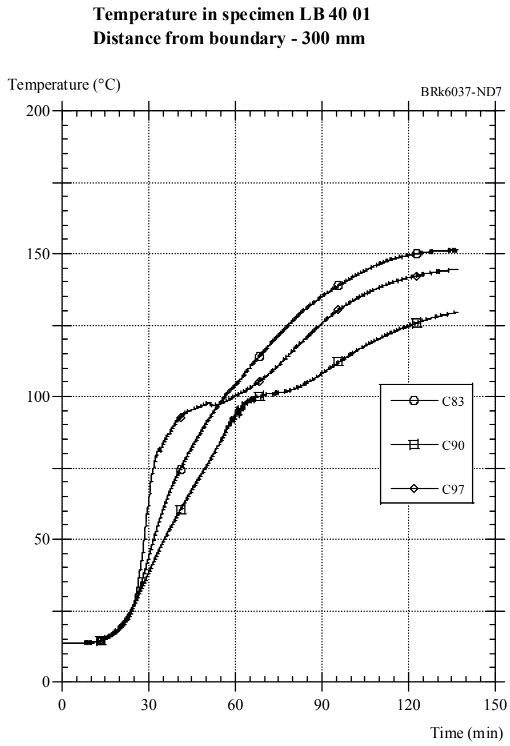

Figure B38. Temperature 300 mm from the edge at 100 mm depth

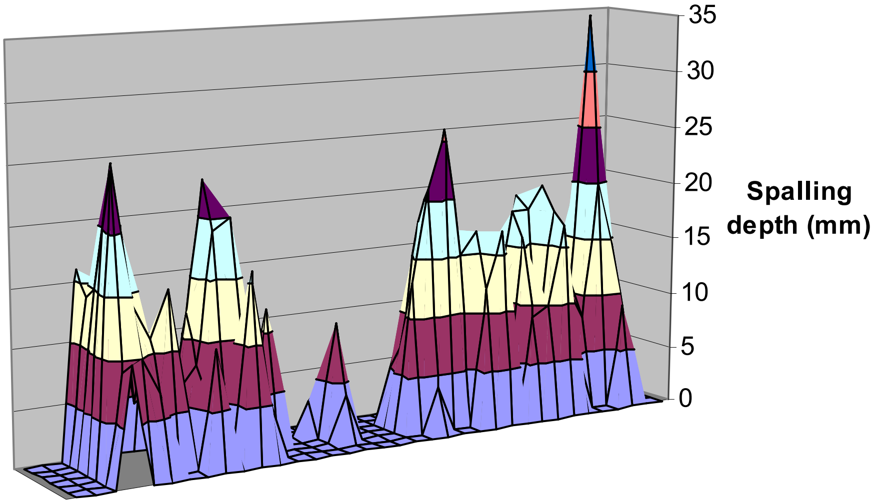

Figure B39. Spalling depth of specimen LB 40 01.

Table B5. Spalling depth of specimen LB 40 01. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	0	100	200	300	400	500	600
0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0
300	10	9	25	20	15	14	16
400	0	10	14	20	25	15	9
500	0	7	11	10	5	10	0
600	0	0	15	7	6	8	0
700	0	0	5	6	4	0	0
800	0	10	6	8	12	7	0
900	0	2	6	19	23	12	0
1000	0	16	10	20	12	0	0
1100	0	5	6	0	0	0	0
1200	0	0	0	12	8	0	0
1300	0	0	0	0	0	0	0
1400	0	0	0	0	0	0	0
1500	0	0	0	0	3	0	0
1600	0	0	4	10	5	0	0
1700	0	0	0	0	0	0	0
1800	0	0	0	0	0	0	0
1900	0	0	0	0	0	0	0
2000	0	0	13	7	5	0	0
2100	0	4	21	18	10	0	0
2200	0	0	26	20	14	0	0
2300	0	0	15	17	4	0	0
2400	0	12	17	10	10	0	0
2500	0	17	15	10	11	9	13
2600	0	0	0	10	14	0	0
2700	0	9	16	18	10	0	0
2800	0	10	7	18	19	4	0
2900	0	17	18	20	5	4	0
3000	0	5	11	6	13	12	12
3100	0	0	8	11	10	10	12
3200	0	0	20	35	20	13	16
3300	0	9	14	18	15	10	0
3400	0	0	0	0	0	0	0
3500	0	0	0	0	0	0	0
3600	0	0	0	0	0	0	0

B7 – Measurements on specimen LB 40 11

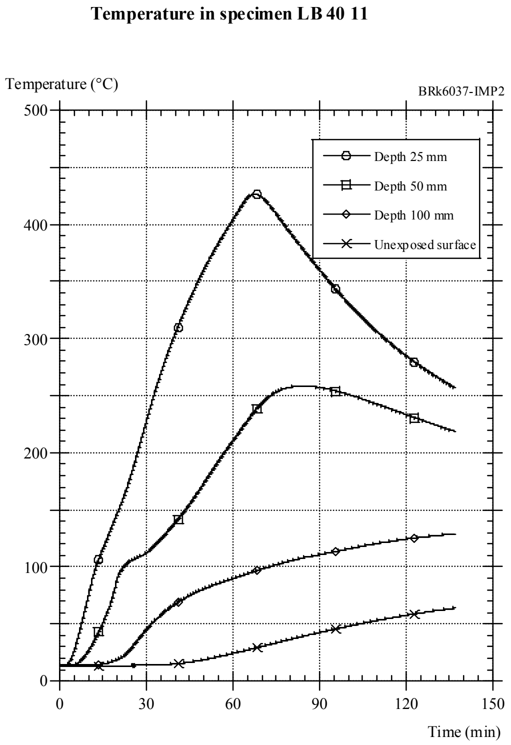

Figure B40. Mean temperature at different depths.

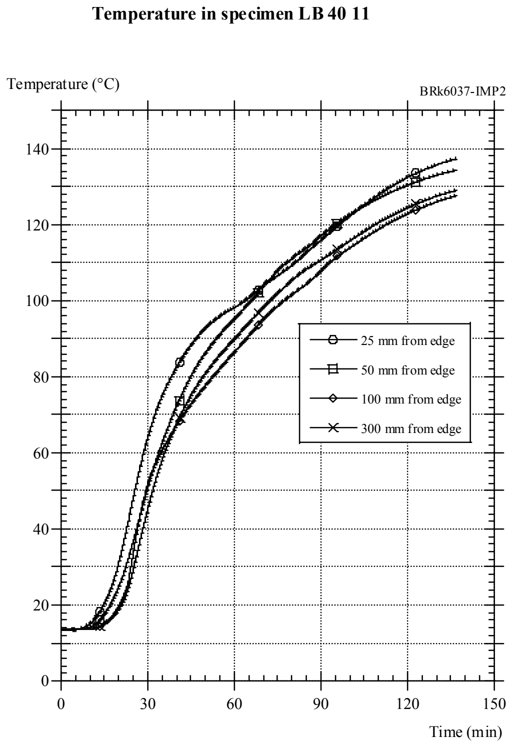

Figure B41. Mean temperature at different positions from the edge

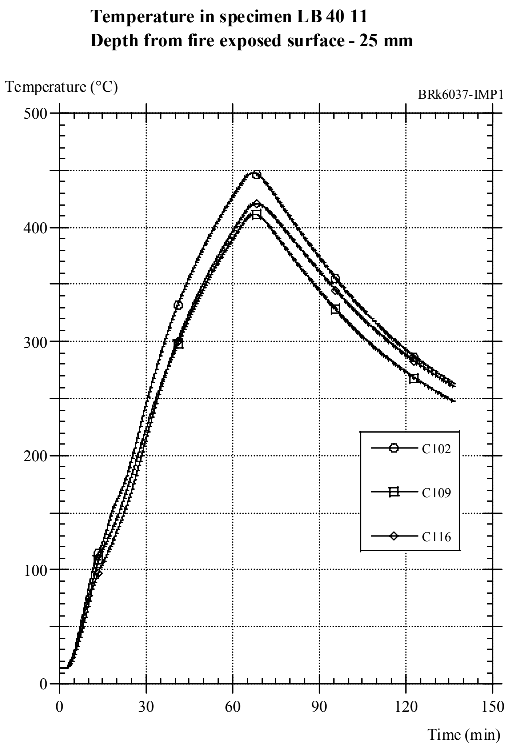

Figure B42. Temperature 25 mm from the exposed surface

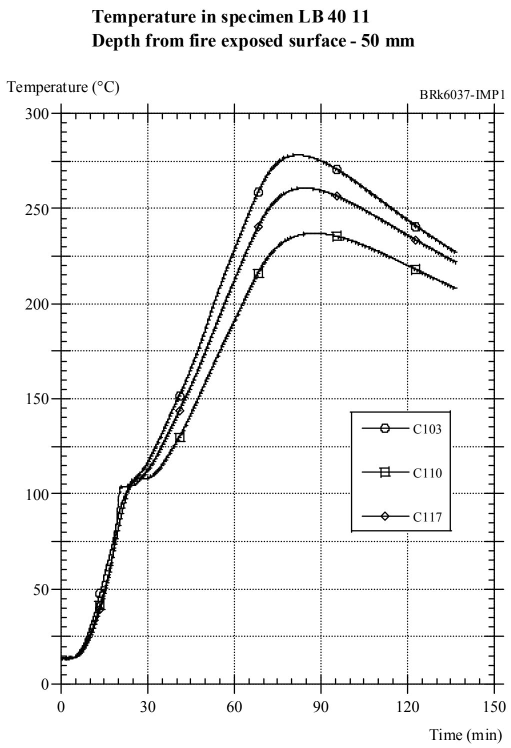

Figure B43. Temperature 50 mm from the exposed surface

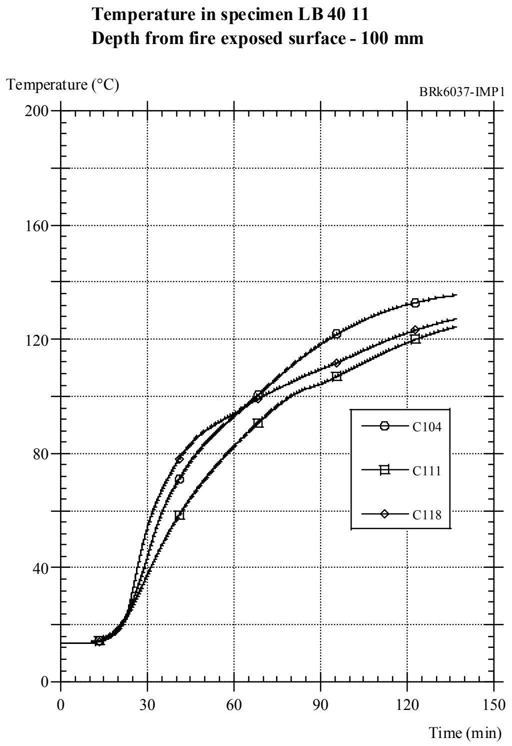

Figure B44. Temperature 100 mm from the exposed surface

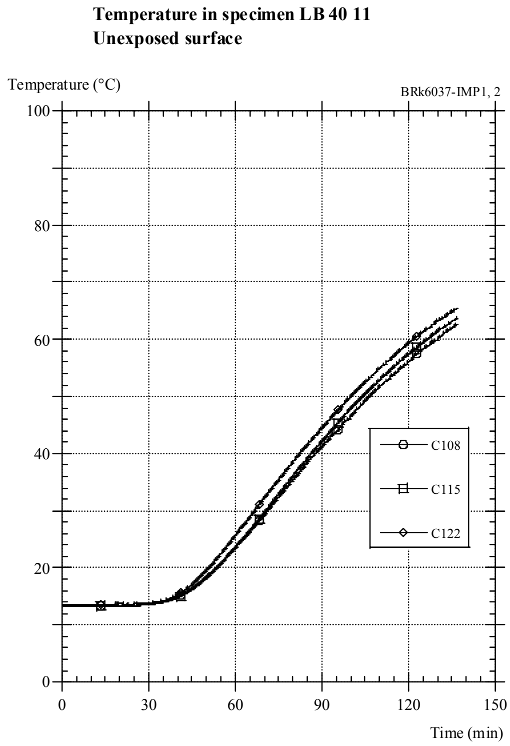

Figure B45. Temperature on the unexposed surface

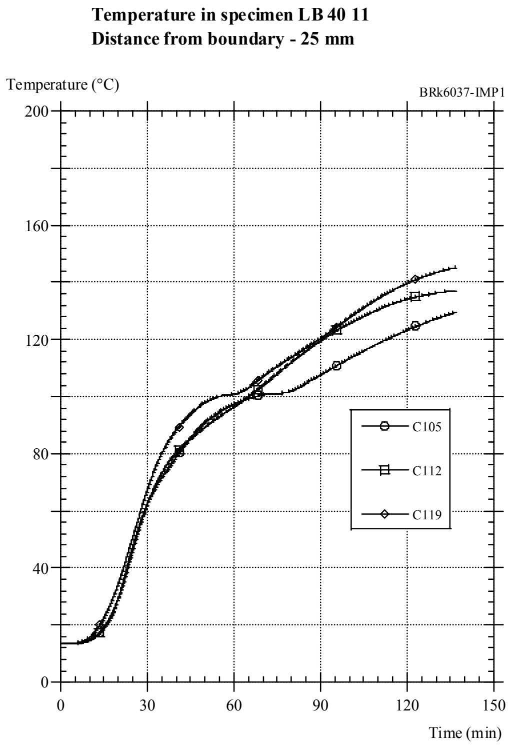

Figure B46. Temperature 25 mm from the edge at 100 mm depth

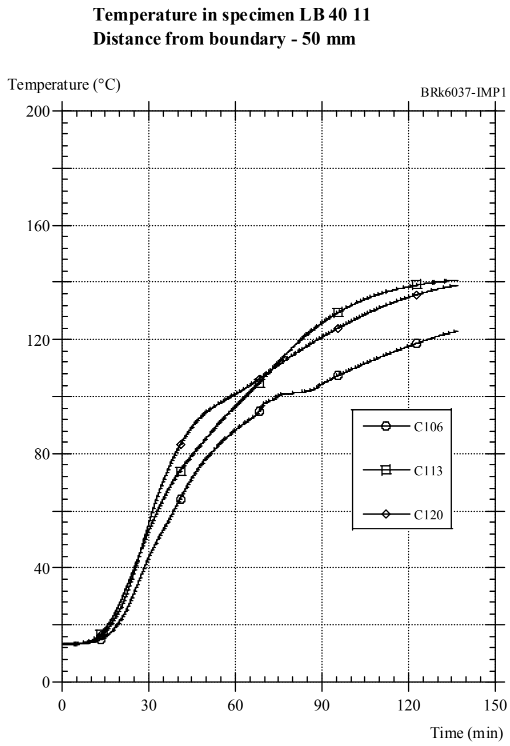

Figure B47. Temperature 50 mm from the edge at 100 mm depth

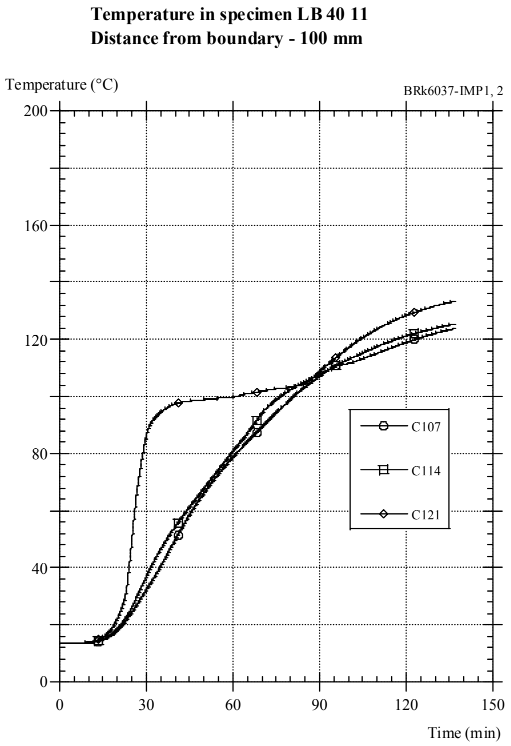

Figure B48. Temperature 100 mm from the edge at 100 mm depth

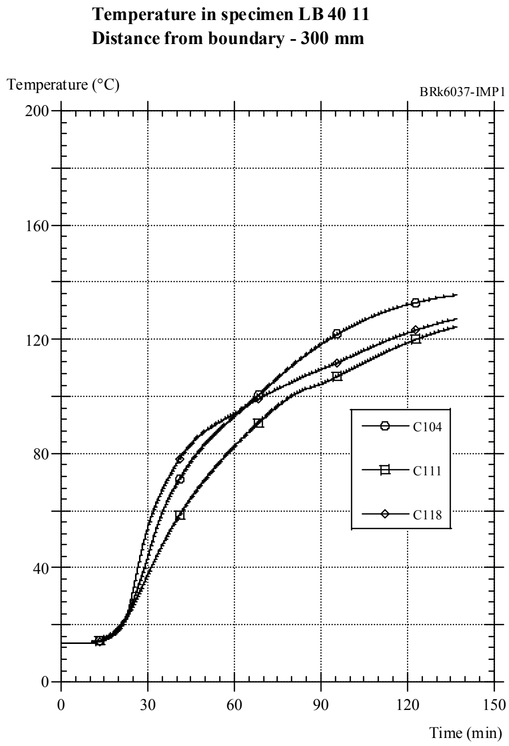

Figure B49. Temperature 300 mm from the edge at 100 mm depth

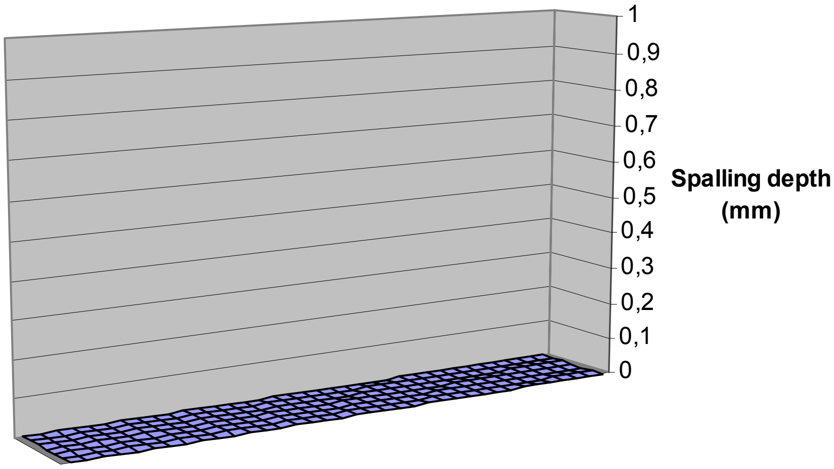

Figure B50. Spalling depth of specimen LB 40 11.

Table B6. Spalling depth of specimen LB 40 11. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	0	100	200	300	400	500	600
0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0
600	0	0	0	0	0	0	0
700	0	0	0	0	0	0	0
800	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0
1100	0	0	0	0	0	0	0
1200	0	0	0	0	0	0	0
1300	0	0	0	0	0	0	0
1400	0	0	0	0	0	0	0
1500	0	0	0	0	0	0	0
1600	0	0	0	0	0	0	0
1700	0	0	0	0	0	0	0
1800	0	0	0	0	0	0	0
1900	0	0	0	0	0	0	0
2000	0	0	0	0	0	0	0
2100	0	0	0	0	0	0	0
2200	0	0	0	0	0	0	0
2300	0	0	0	0	0	0	0
2400	0	0	0	0	0	0	0
2500	0	0	0	0	0	0	0
2600	0	0	0	0	0	0	0
2700	0	0	0	0	0	0	0
2800	0	0	0	0	0	0	0
2900	0	0	0	0	0	0	0
3000	0	0	0	0	0	0	0
3100	0	0	0	0	0	0	0
3200	0	0	0	0	0	0	0
3300	0	0	0	0	0	0	0
3400	0	0	0	0	0	0	0
3500	0	0	0	0	0	0	0
3600	0	0	0	0	0	0	0

B8 - Measurements on small slabs of self-compacting concrete

Table B7. Observations during the fire test of specimen SS 30 01.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Start of test
9:55	Spalling starts. One small explosion.
11:10	One explosion
11:50	A loud explosion
12:30	Repeated explosions
13:45	Explosions with an interval between 10 to 30 seconds
15:40	Explosions with an interval between 5 to 15 seconds
21:50	A loud explosion
22:30	Water is pouring out from surface cracks
24:25	A loud explosion
26:20	Large crack is formed
28:10	Explosions with an interval between 10 to 30 seconds
32:15	The spalling diminish
34:45	The spalling has stopped
45:00	Test is terminated

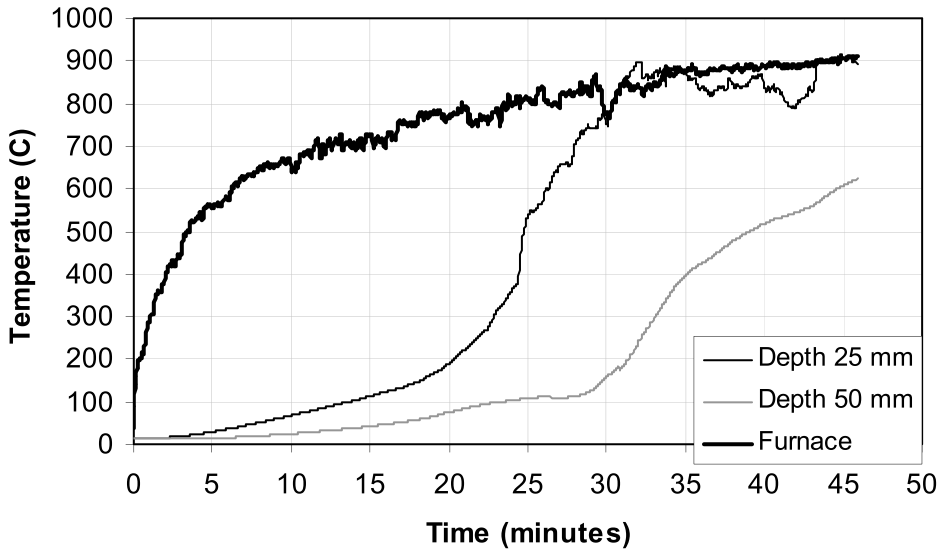

Figure B51. Furnace temperature and temperatures in specimen SS 30 01. The specimen was unloaded during the test.

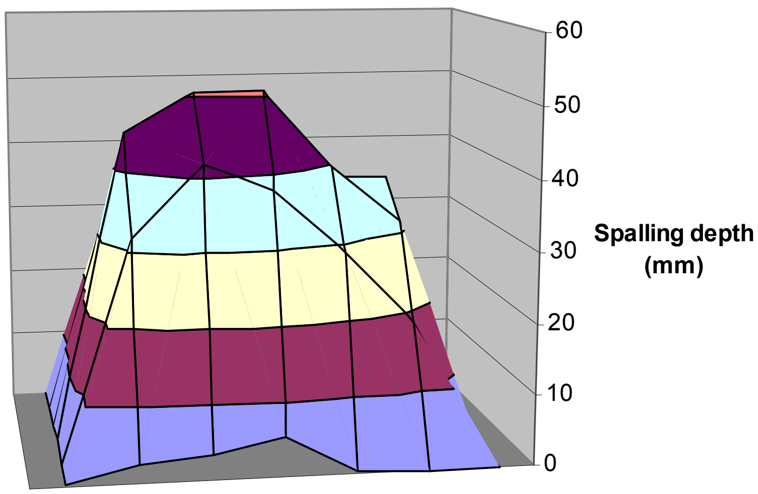

Figure B52. Spalling depth of specimen SS 30 01.

Table B8. Spalling depth of specimen SS 30 01. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	1	0	0	0
120	3	32	45	38	34	0
210	4	42	51	47	36	1
300	6	38	51	43	34	0
390	0	29	40	37	32	0
480	0	19	32	37	31	0
570	0	0	0	0	0	0

Table B9. Observations during the fire test of specimen SS 30 02.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Start of test
7:40	Spalling starts. Faint sound
8:30	Loud explosion
8:50	Small explosion
9:25	Two loud explosions
10:10	Small explosion
10:55	Two explosions
11:20	Three loud explosions
11:40	Two loud explosions
12:05	Two small explosions
12:30	Loud explosion
12:50	Small explosion
13:15	Two explosions
13:30	Three explosions
13:40	One explosion
14:15	Two explosions
14:30	One explosion
14:55	One explosion
15:15	Two explosions
15:35	Loud explosion
16:10	Explosions at an interval of 10 to 15 seconds
26:05	The amount of spalling diminish. Water is pouring out from the surface
31:50	The spalling has stopped
50:00	Test is terminated

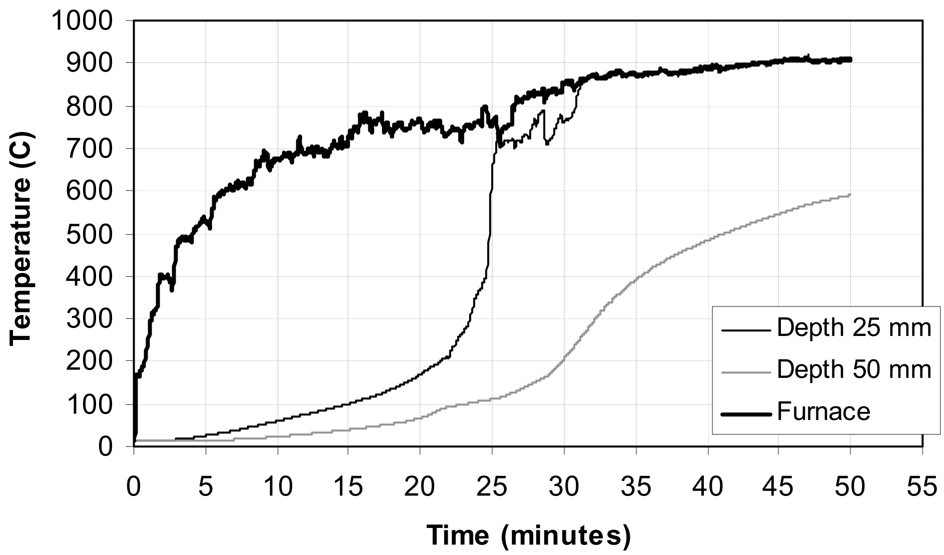

Figure B53. Furnace temperature and temperatures in specimen SS 30 02. The specimen was unloaded during the test.

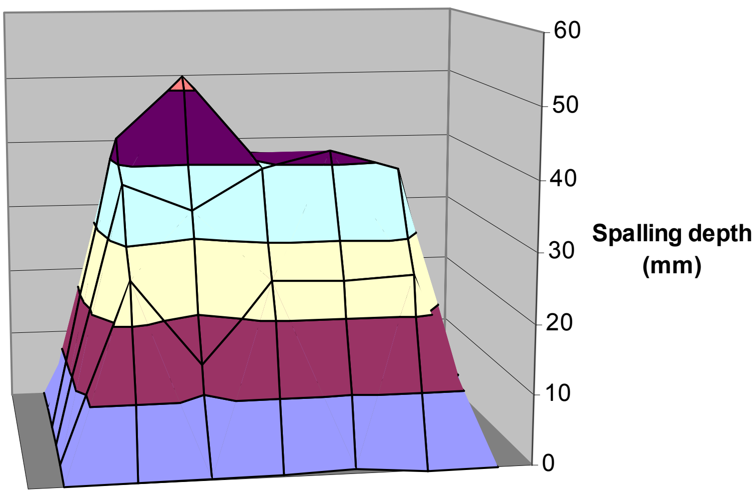

Figure B54. Spalling depth of specimen SS 30 02.

Table B10. Spalling depth of specimen SS 30 02. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	0	0	0	0
120	0	26	38	43	24	0
210	0	14	34	52	19	0
300	0	25	40	41	16	0
390	1	25	42	40	31	0
480	0	26	39	28	28	0
570	0	0	0	2	1	0

Table B11. Observations during the fire test of specimen SS 30 03.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Start of test
9:25	Spalling starts
	The spalling is loud and heavy. The furnace is quickly filled with debris. It was not possible to take more observations since the debris had to be removed during the test.
45:00	Test is terminated

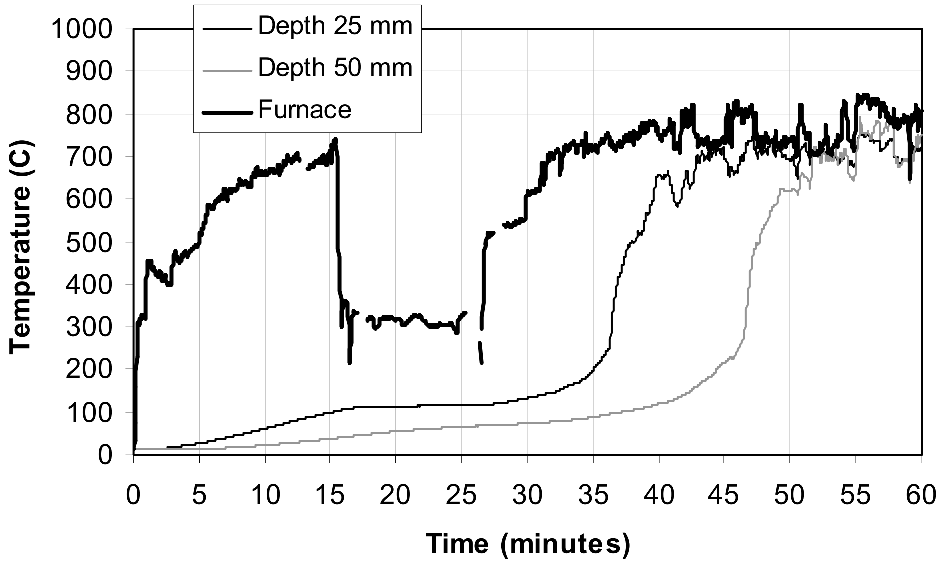

Figure B55. Furnace temperature and temperatures in specimen SS 30 03. The specimen was loaded in compression during the test. The furnace was filled with concrete due to the heavy spalling. Hence it was not possible for the burner to heat enough during a period when the furnace was cleaned from the debris.

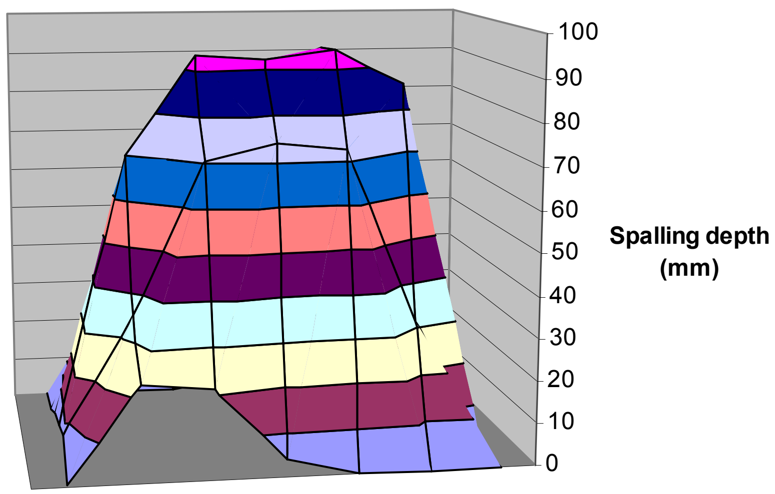

Figure B56. Spalling depth of specimen SS 30 03.

Table B12. Spalling depth of specimen SS 30 03. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	1	7	5	4	0	0
120	23	35	70	51	34	0
210	21	70	93	84	63	0
300	4	75	92	87	61	3
390	0	72	94	93	67	0
480	0	32	86	82	39	0
570	0	0	3	1	0	0

Table B13. Observations during the fire test of specimen SS 30 04.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Start of test
6:00	Spalling starts
6:35	Small explosion
8:00	Loud explosion
10:40	Two small explosions
12:30	Repeated small explosions
12:50	Loud explosion
13:50	Small explosions with an interval between 5 to 15 seconds
15:00	Small explosions with an interval between 2 to 5 seconds
19:00	The explosions are louder
20:10	Loud explosions
22:15	Very loud explosion
23:10	Loud explosions with an interval of 10 seconds
25:00	Water is pouring out on the surface at cracks
43:10	The loud explosions continues
52:10	The intensity of the spalling diminish
65:40	The spalling has stopped
75:00	Test is terminated

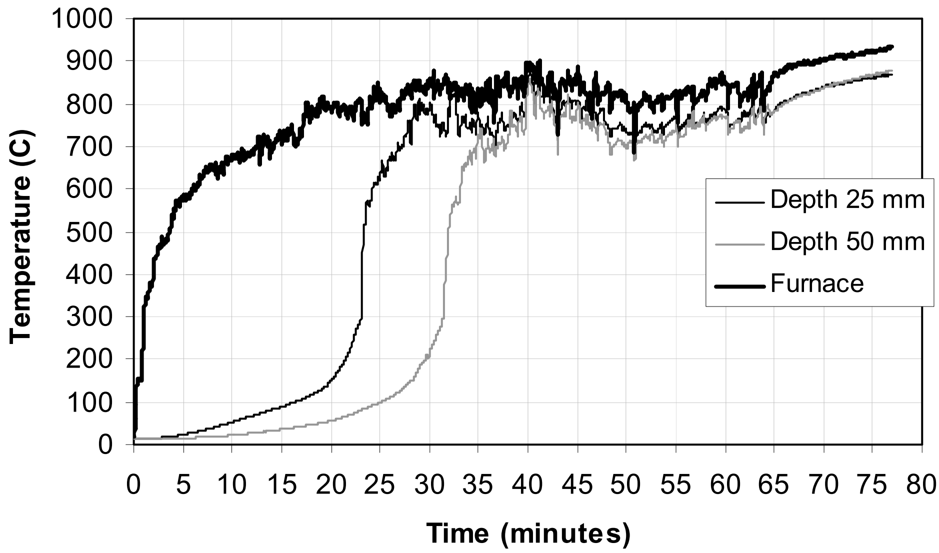

Figure B57. Furnace temperature and temperatures in specimen SS 30 04. The specimen was loaded in compression during the test.

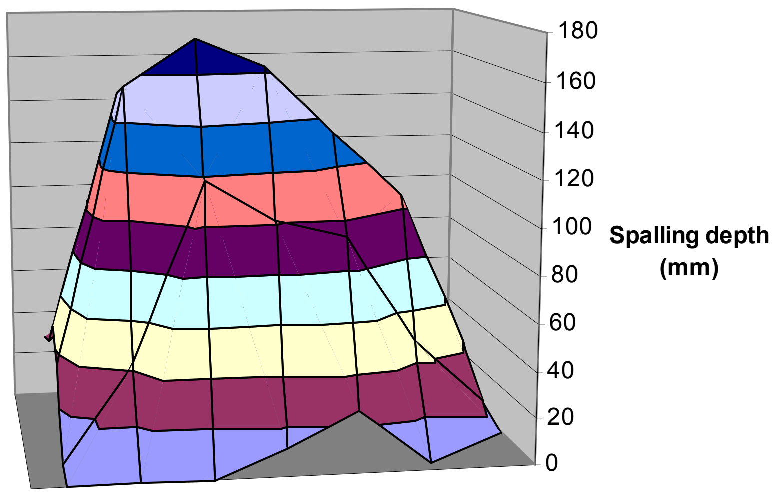

Figure B58. Spalling depth of specimen SS 30 04.

Table B14. Spalling depth of specimen SS 30 04. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	36	46	33	27
120	0	43	155	149	59	24
210	0	119	175	161	39	4
300	12	101	163	157	41	0
390	26	94	134	132	44	0
480	3	48	106	86	41	0
570	15	20	37	31	8	0

Table B15. Observations during the fire test of specimen SS 40 01.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Start of test
10:15	Loud explosion
11:00	Small explosion
11:20	Small explosions with interval between 10 to 20 seconds
14:00	Two loud explosions
14:15	Loud explosion
14:50	Loud explosion
15:00	Loud explosion
	Loud explosions at interval between 10 to 20 seconds
	Small explosions at interval between 0 to 15 seconds
17:00	Cracks on both short sides
18:00	Crack at one long side
23:00	Water is pouring out from the cracks
25:00	Spalling diminish
29:30	Spalling has stopped
35:50	Test is terminated

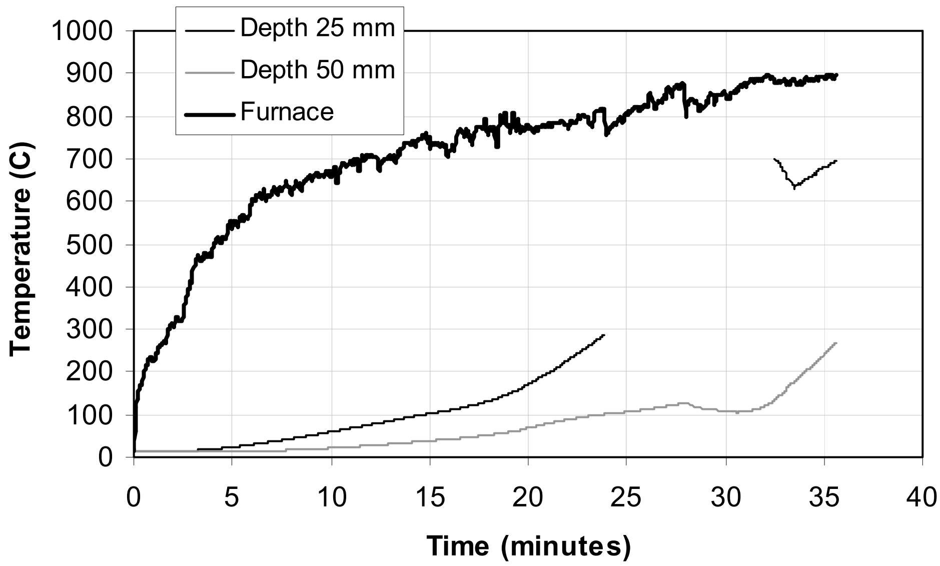

Figure B59. Furnace temperature and temperatures in specimen SS 40 01. The specimen was unloaded during the test. The thermocouple at depth 25 mm was out of function from 23 minutes to 33 minutes.

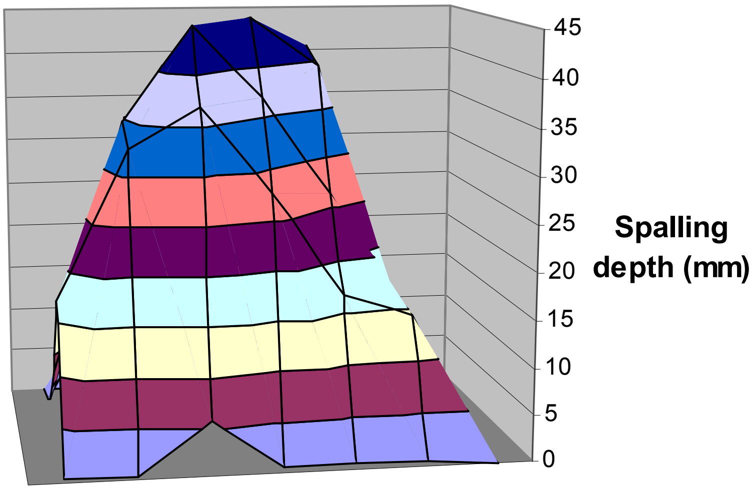

Figure B60. Spalling depth of specimen SS 40 01.

Table B16. Spalling depth of specimen SS 40 01. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	17	8	3	1	0
120	0	33	35	29	13	0
210	6	37	45	43	29	0
300	1	28	37	45	37	0
390	1	17	26	40	41	9
480	1	14	14	9	15	0
570	0	0	0	0	0	0

Table B17. Observations during the fire test of specimen SS 40 02.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Start of test
10:45	Spalling starts with small explosion
11:35	Small explosion
11:55	Explosion
12:30	Two explosions
13:30	Small explosions
13:55	Loud explosion
14:30	Small explosion
15:30	Intensity increases. Interval between explosions is 5 to 10 seconds
16:15	Loud explosion
16:55	Loud explosion
17:15	Interval increases to between 2 and 5 seconds
18:30	Loud explosion
19:00	Interval between explosions decreases
21:00	Interval between explosions increases to 5 to 10 seconds
22:50	Loud explosion
24:00	Cracks on the sides
30:00	Spalling has stopped
36:00	Test is terminated

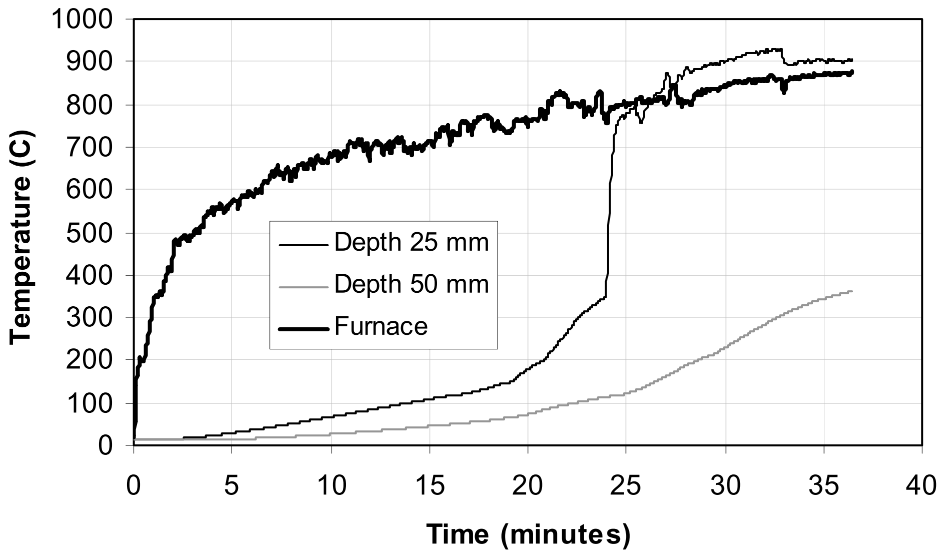

Figure B61. Furnace temperature and temperatures in specimen SS 40 02. The specimen was unloaded during the test.

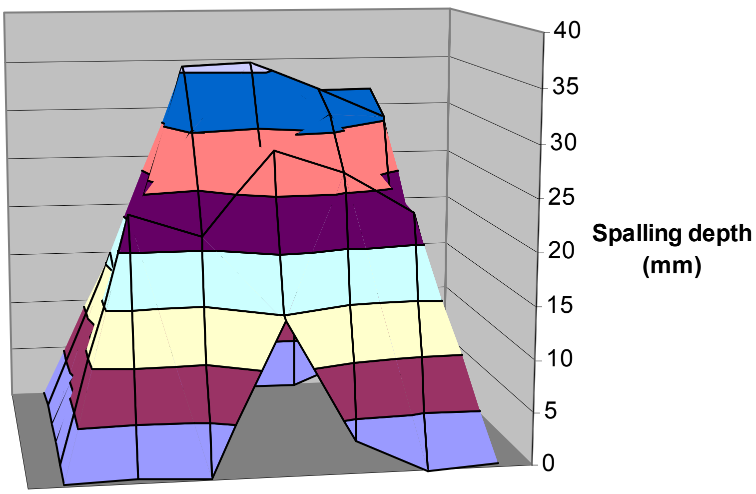

Figure B62. Spalling depth of specimen SS 40 02.

Table B18. Spalling depth of specimen SS 40 02. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	0	0	1	0
120	0	23	18	14	16	0
210	0	21	30	36	18	0
300	15	29	27	36	23	0
390	3	27	32	33	32	0
480	0	23	16	30	32	3
570	0	0	0	0	0	0

Table B19. Observations during the fire test of specimen SS 40 03.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Start of test
9:15	Explosion
10:05	Some small explosions
12:30	Explosion
14:00	Interval between explosions is 10 to 30 seconds
15:20	Interval between explosions is 5 to 15 seconds
18:00	The explosions are louder
19:45	Very loud explosion The spalling continues with interval between 5 to 15 seconds
27:30	Water start pouring on the unexposed surface
35:00	Water start pouring in cracks on the sides
42:35	Very loud explosions
47:00	Loud explosions. A wide crack is formed on the side close to the fire exposed surface
58:00	Spalling has stopped
63:30	Test is terminated

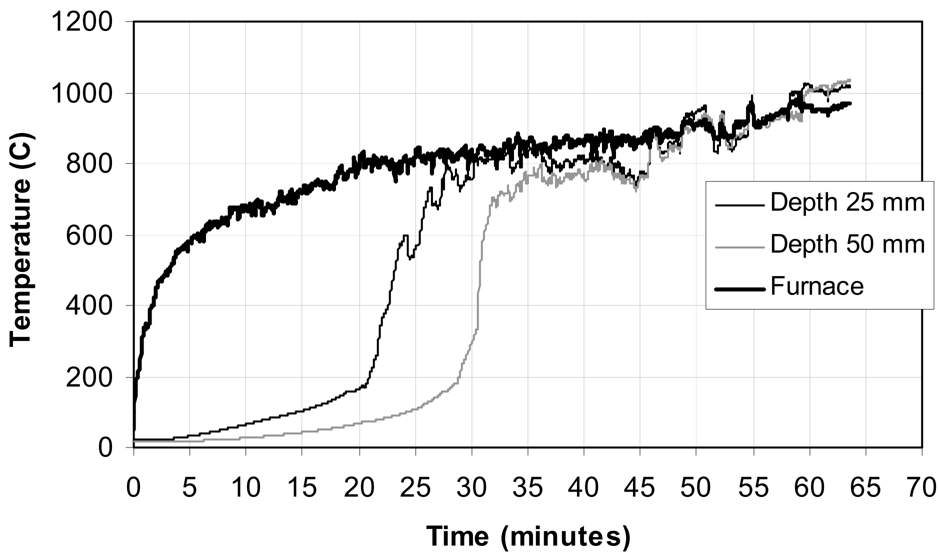

Figure B63. Furnace temperature and temperatures in specimen SS 40 03. The specimen was loaded in compression during the test.

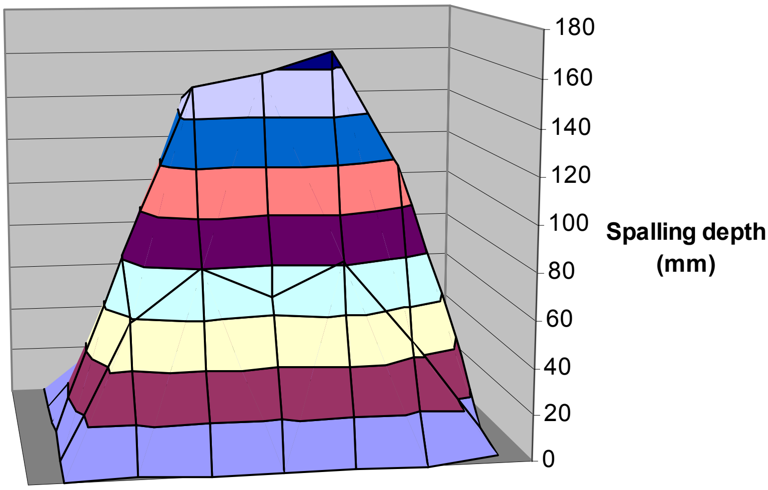

Figure B64. Spalling depth of specimen SS 40 03.

Table B20. Spalling depth of specimen SS 40 03. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	5	0	0	0
120	2	58	81	43	34	0
210	0	80	153	145	48	0
300	0	67	158	144	63	0
390	0	82	167	148	73	0
480	0	47	117	111	47	0
570	3	7	31	27	14	0

Table B21. Observations during the fire test of specimen SS 40 04.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Start of test
7:40	Explosion
13:10	Interval between explosions is 15 to 20 seconds
14:00	Interval between explosions is 5 to 10 seconds
25:50	Water starts pouring in a crack on one side
34:50	Very loud explosion
43:40	Very loud explosion
64:10	Spalling has stopped
67:00	Test is terminated

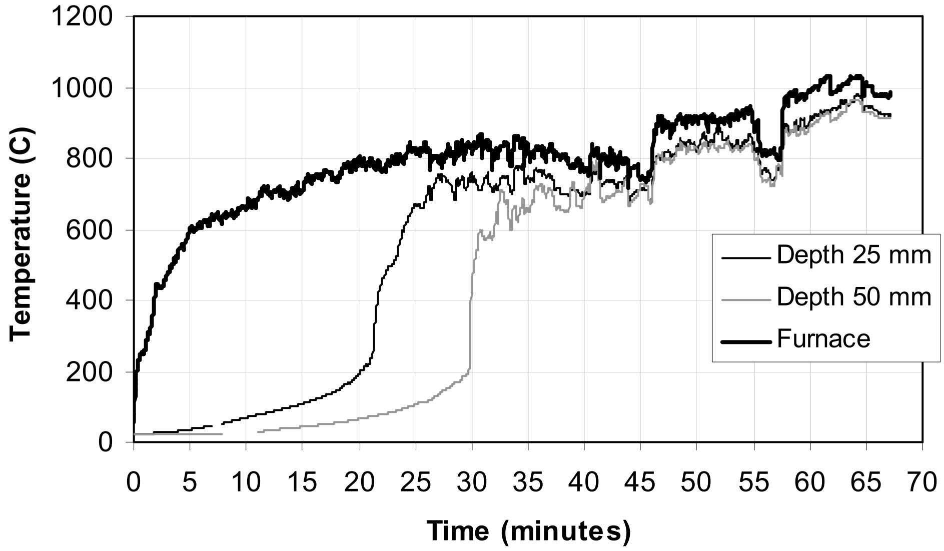

Figure B65. Furnace temperature and temperatures in specimen SS 40 04. The specimen was loaded in compression during the test.

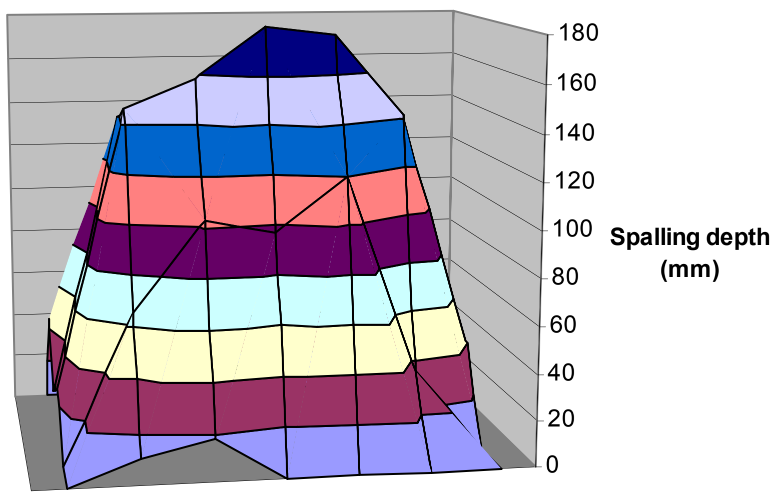

Figure B66. Spalling depth of specimen SS 40 04.

Table B22. Spalling depth of specimen SS 40 04. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	26	18	44	0
120	11	65	147	140	38	0
210	18	103	159	150	61	4
300	0	97	180	158	58	0
390	0	120	177	157	64	0
480	0	36	141	120	53	0
570	0	0	41	33	15	0

Table B23. Observations during the fire test of specimen SS 40 11.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Test is started
24:35	Cracks have formed on the sides
30:00	Test is terminated

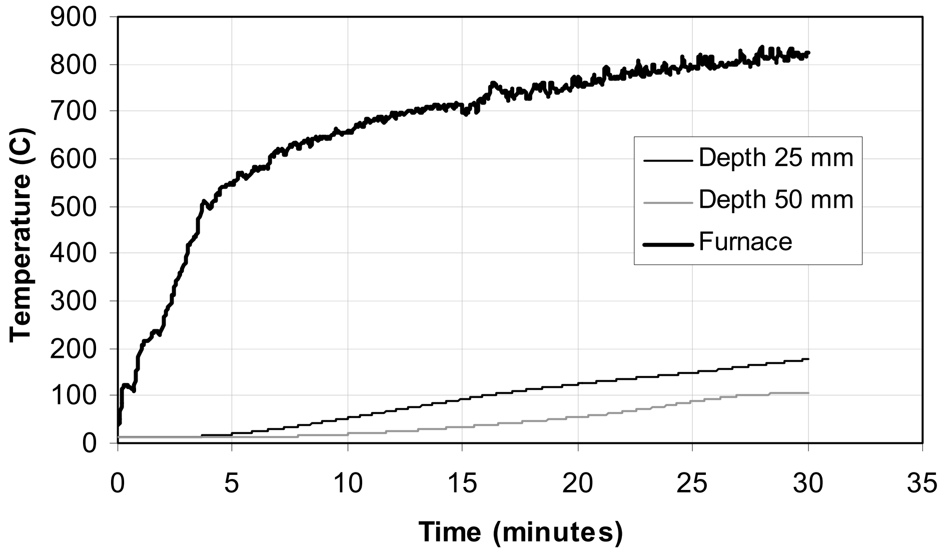

Figure B67. Furnace temperature and temperatures in specimen SS 40 11. The specimen was unloaded during the test.

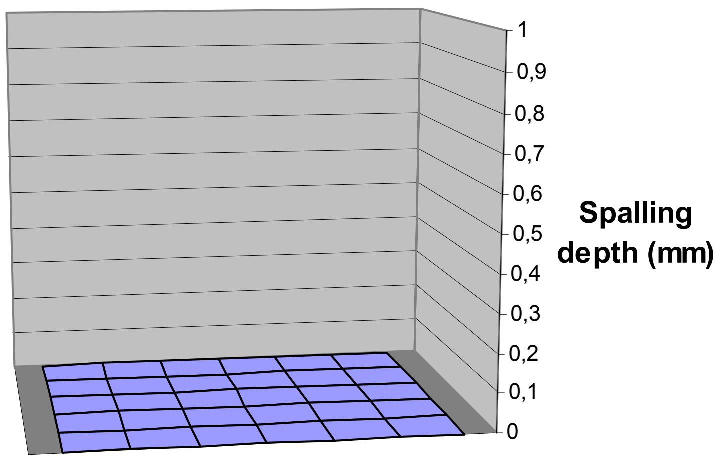

Figure B68. Spalling depth of specimen SS 40 11.

Table B24. Spalling depth of specimen SS 40 11. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	0	0	0	0
120	0	0	0	0	0	0
210	0	0	0	0	0	0
300	0	0	0	0	0	0
390	0	0	0	0	0	0
480	0	0	0	0	0	0
570	0	0	0	0	0	0

Table B25. Observations during the fire test of specimen SS 40 12.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Test is started
9:55	Small cracks have formed on the sides
30:00	Test is terminated

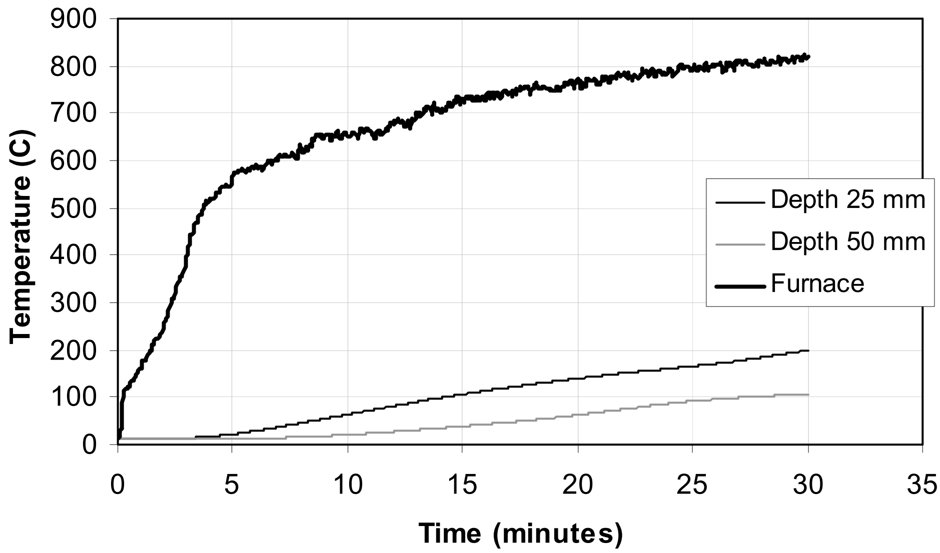

Figure B69. Furnace temperature and temperatures in specimen SS 40 12. The specimen was unloaded during the test.

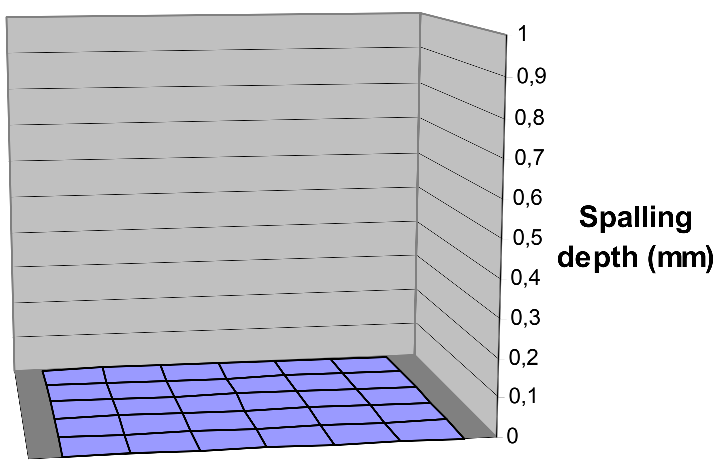

Figure B70. Spalling depth of specimen SS 40 12.

Table B26. Spalling depth of specimen SS 40 12. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	0	0	0	0
120	0	0	0	0	0	0
210	0	0	0	0	0	0
300	0	0	0	0	0	0
390	0	0	0	0	0	0
480	0	0	0	0	0	0
570	0	0	0	0	0	0

Table B27. Observations during the fire test of specimen SS 40 13.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Test is started
30:00	Test is terminated

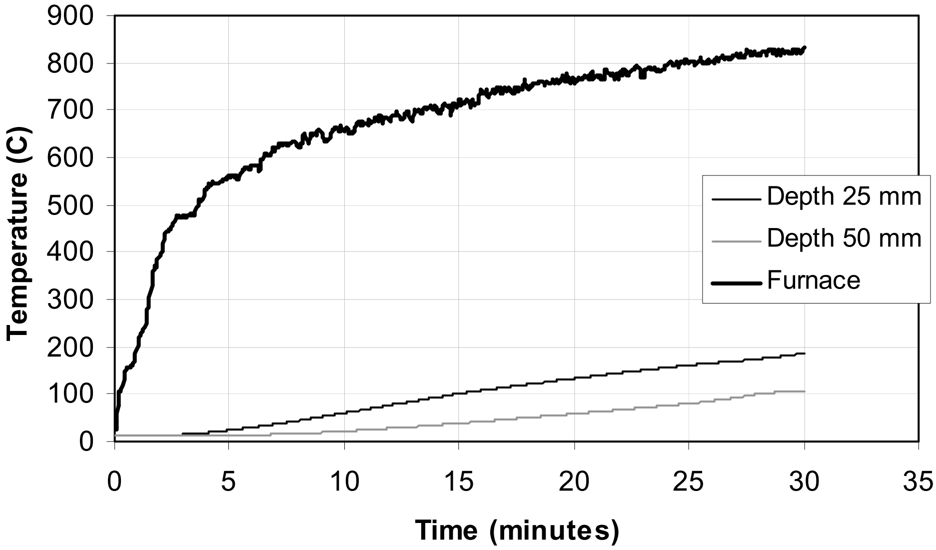

Figure B71. Furnace temperature and temperatures in specimen SS 40 13. The specimen was loaded in compression during the test.

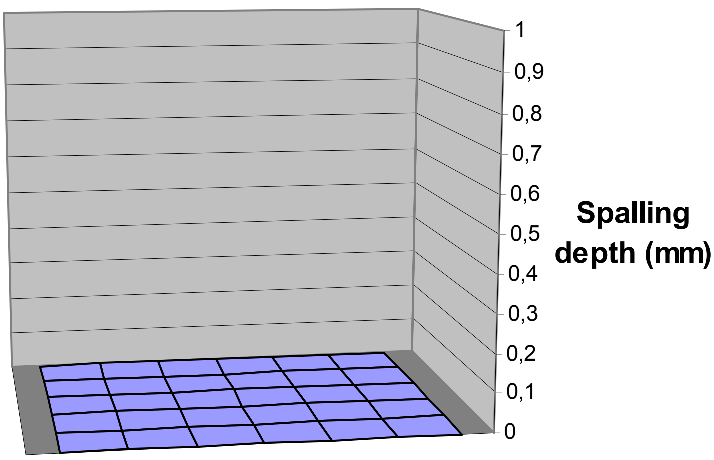

Figure B72. Spalling depth of specimen SS 40 13.

Table B28. Spalling depth of specimen SS 40 13. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	0	0	0	0
120	0	0	0	0	0	0
210	0	0	0	0	0	0
300	0	0	0	0	0	0
390	0	0	0	0	0	0
480	0	0	0	0	0	0
570	0	0	0	0	0	0

Table B29. Observations during the fire test of specimen SS 40 14.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Test is started
24:15	Water is pouring on the sides
30:00	Test is terminated

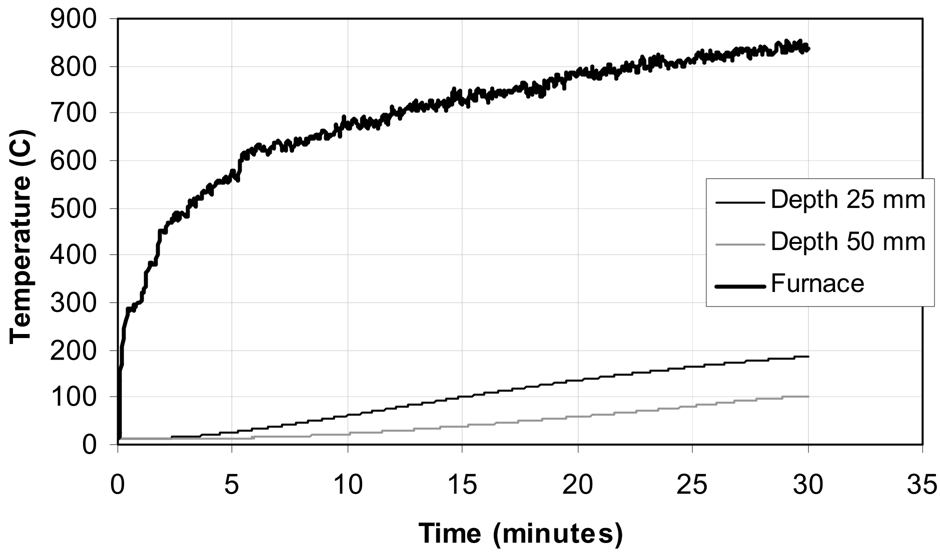

Figure B73. Furnace temperature and temperatures in specimen SS 40 14. The specimen was loaded in compression during the test.

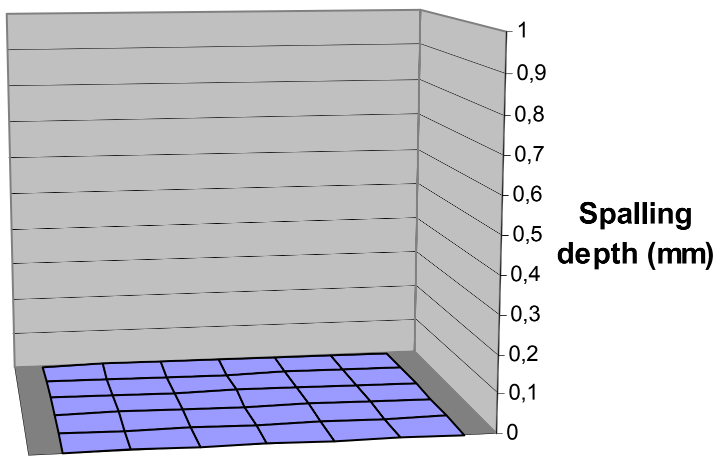

Figure B74. Spalling depth of specimen SS 40 14.

Table B30. Spalling depth of specimen SS 40 14. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	0	0	0	0
120	0	0	0	0	0	0
210	0	0	0	0	0	0
300	0	0	0	0	0	0
390	0	0	0	0	0	0
480	0	0	0	0	0	0
570	0	0	0	0	0	0

Table B31. Observations during the fire test of specimen SS 55 01.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Test is started
12:00	Cracks have formed on the sides
12:20	Very loud explosion
15:00	Two explosions
15:45	Loud explosion
16:05	Explosion
16:10	Explosion
16:55	Two explosions
17:25	Small explosion
17:45	Small explosion
18:05	Two small explosions
18:50	Two small explosions
20:30	Two explosions
21:40	Two explosions
23:00	Explosion
25:40	Explosion Spalling has stopped
31:00	Test is terminated

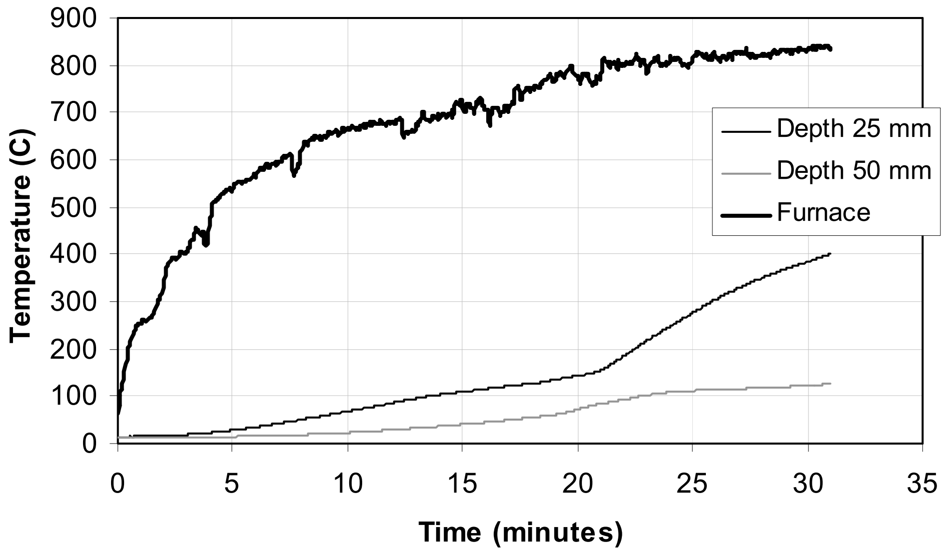

Figure B75. Furnace temperature and temperatures in specimen SS 55 01. The specimen was unloaded during the test.

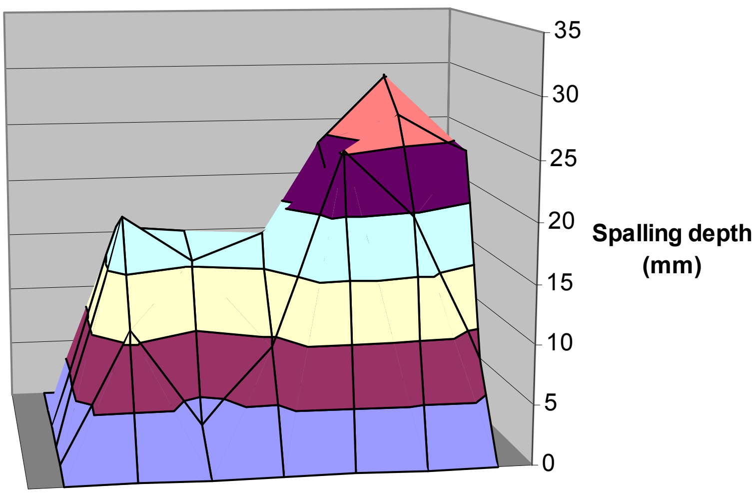

Figure B76. Spalling depth of specimen SS 55 01.

Table B32. Spalling depth of specimen SS 55 01. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	0	0	0	0
120	0	11	19	18	0	0
210	0	3	15	17	0	0
300	0	9	18	10	7	0
390	0	25	21	24	12	0
480	0	20	27	30	15	0
570	0	8	24	17	0	0

Table B33. Observations during the fire test of specimen SS 55 02.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Test is started
11:25	Small explosion
14:20	Loud explosion
14:50	Small explosion
15:50	Loud explosion
16:05	Small explosion
16:25	Small explosion
16:55	Small explosion
18:00	Explosion
18:20	Explosion Cracks have formed on sides
19:45	Small explosion
19:50	Explosion
20:35	Loud explosion
20:50	Small explosion
21:10	Explosion
21:15	Explosion
21:35	Explosion
23:10	Explosion
24:10	Small explosion
24:50	Explosion
27:10	Explosion Spalling has stopped
33:00	Test is terminated

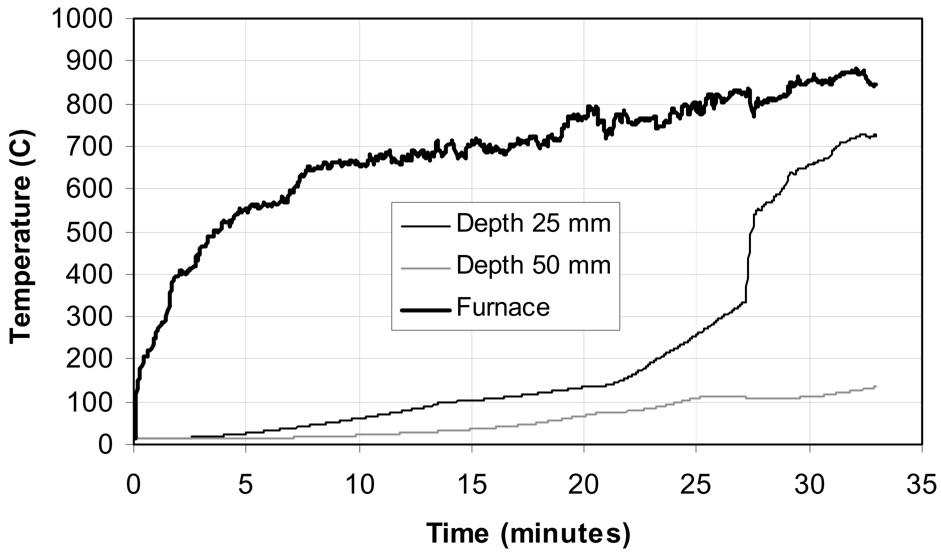

Figure B77. Furnace temperature and temperatures in specimen SS 55 02. The specimen was unloaded during the test.

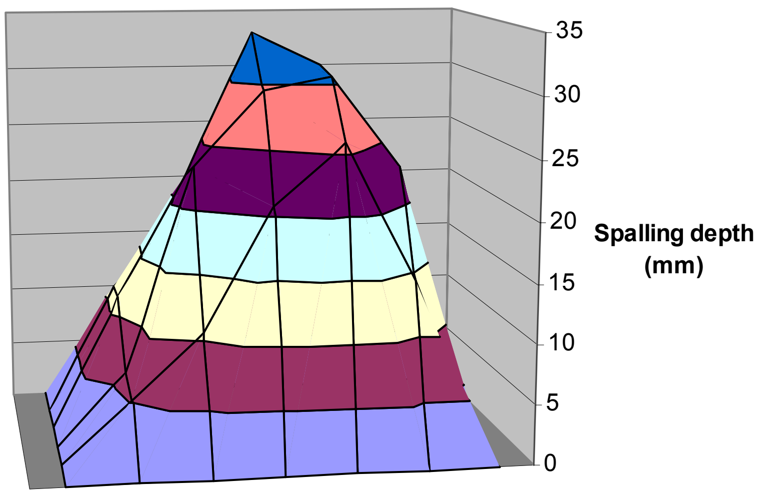

Figure B78. Spalling depth of specimen SS 55 02.

Table B34. Spalling depth of specimen SS 55 02. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	0	0	0	0
120	0	5	6	11	11	0
210	0	11	23	22	17	0
300	0	21	30	34	23	0
390	0	26	31	31	16	0
480	0	14	23	18	21	0
570	0	0	0	0	0	0

Table B35. Observations during the fire test of specimen SS 55 03. Extensive protocol.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Test is started
12:00	Loud explosion
12:55	Loud explosion
13:00	Explosion
13:15	Two small explosions
13:40	Small explosion
14:25	Two loud explosions
14:40	Loud explosion
15:30	Loud explosion
15:45	Small explosion
16:15	Small explosion
16:20	Small explosion
17:10	Small explosion
17:15	Two loud explosions
18:05	Small explosion
18:15	Small explosion
18:20	Loud explosion
18:55	Loud explosion
19:00	Small explosion
19:15	Loud explosion
19:45	Loud explosion
19:50	Small explosion
20:00	Small explosion
20:05	Small explosion
20:35	Two explosions
20:45	Loud explosion
21:35	Two explosions
22:10	Two loud explosions
22:15	Two loud explosions
23:05	Loud explosion
23:15	Loud explosion
24:35	Loud explosion
24:50	Small explosion
25:10	Small explosion
25:20	Small explosion
25:25	Two small explosions
25:40	Small explosion
25:55	Small explosion
26:10	Explosion
26:15	Three loud explosions
26:45	Small explosion
27:00	Three explosions
27:20	Small explosion
27:35	Small explosion
27:55	Small explosion
28:00	Explosion
28:05	Small explosion
28:20	Two small explosions
28:25	Two explosions

Table B35 cont. Observations during the fire test of specimen SS 55 03. Extensive protocol.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
29:05	Loud explosion
29:20	Three small explosions
29:40	Loud explosion
29:50	Two loud explosions
30:05	Three small explosions
30:40	Loud explosion
30:45	Water is pouring on the unexposed face
31:10	Explosion
31:25	Explosion
31:55	Loud explosion
32:20	Explosion
33:45	Loud explosion
34:20	Loud explosion
34:25	Loud explosion
34:40	Loud explosion
35:30	Loud explosion
35:50	Small explosion
36:15	Explosion
36:20	Two small explosions
36:55	Small explosion
37:20	Loud explosion
38:20	Explosion
39:00	Explosion
39:35	Small explosion
41:20	Very loud explosion A large crack was formed on one side all the way into the furnace
42:00	Explosion
42:10-42:35	Small explosions with interval 3 seconds
42:55	Loud explosion
43:15	Three small explosions
43:45	Small explosion
44:05	Two small explosions
44:20	Explosion
44:35	Explosion
45:00	Two small explosions
45:40	Two loud explosions
46:20	Two small explosions
46:25	Two explosions
47:00	Small explosion
47:20	Small explosion
47:35	Explosion
47:45	Explosion
48:30	Explosion
49:30	Loud explosion
50:10	Loud explosion
50:50	Loud explosion
52:10	Explosion
53:30	Small explosion. Spalling has stopped
59:00	Test is terminated

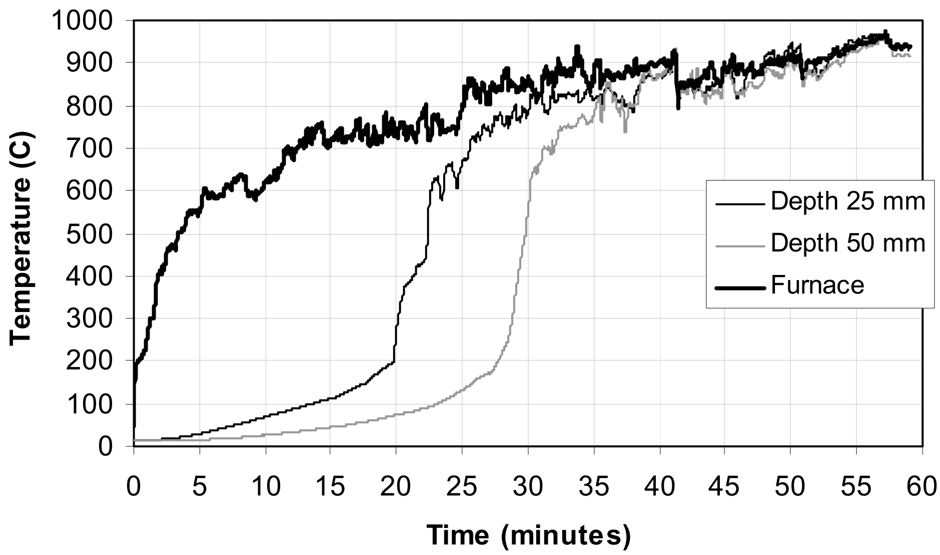

Figure B79. Furnace temperature and temperatures in specimen SS 55 03. The specimen was loaded in compression during the test.

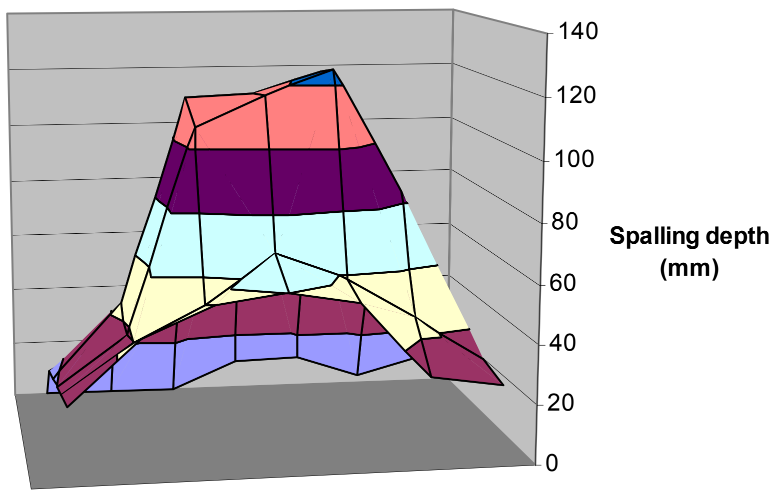

Figure B80. Spalling depth of specimen SS 55 03.

Table B36. Spalling depth of specimen SS 55 03. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	26	24	21	18	15	0
120	47	40	38	43	28	0
210	57	52	107	114	47	0
300	60	68	117	116	99	10
390	56	59	125	123	81	10
480	31	45	84	83	55	3
570	27	30	25	23	23	8

Table B37. Observations during the fire test of specimen SS 55 04. Extensive protocol.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
0:00	Test is started
8:35	Loud explosion
10:15	Loud explosion
11:55	Loud explosion
12:55	Two loud explosions
13:40	Loud explosion
14:40	Small explosion
14:55	Two small explosions
16:10	Two loud explosions
17:30	Small explosion
17:50	Small explosion
18:20	Three loud explosions
18:40	Small explosion
19:05	Small explosion
19:15	Small explosion
19:35	Three small explosions
19:55	Small explosion
20:20-22:30	Small explosions with interval of 10 seconds
20:55	Loud explosion
21:10	Loud explosion
21:20	Loud explosion
21:35	Loud explosion
22:30	Small explosion
22:45	Small explosion
23:00	Small explosion
23:10	Loud explosion
23:45	Two small explosions
24:00	Two small explosions
24:10	Crack visible on one side
24:25	Loud explosion
24:40	Loud explosion
25:30	Small explosion
25:35	Loud explosion
26:10	Loud explosion
26:30	Loud explosion
27:10	Loud explosion
27:30	Small explosion
27:55	Small explosion
28:15-28:45	Small explosions with interval of 5 seconds
28:55	Small explosion
29:05	Small explosion
29:10	Loud explosion
29:35	Small explosion
30:00	Two small explosions
30:45	Small explosion
30:50	Small explosion
30:55	Loud explosion
32:00	Water is pouring out on the unexposed surface
32:30	Small explosion

Table B37 cont. Observations during the fire test of specimen SS 55 04. Extensive protocol.

Time min:s	*Observations (the observations refer to the exposed side if nothing else is stated)*
32:55	Loud explosion
33:25	Loud explosion and two small explosions
34:05	Small explosion
34:35	Two loud explosions
35:20	Small explosion
37:10	Two loud explosions
38:10	Small explosion
38:55	Loud explosion
39:35	Small explosion
40:25	Crack has formed on one side
40:55	Very loud explosion
41:35	Small explosion
42:15	Two small explosions
43:45	Loud explosion
44:55	Loud explosion
45:30	Small explosion
46:15	Loud explosion
47:45	Small explosion
48:05	Loud explosion
48:55	Three small explosions
49:30	Loud explosion
50:20	Small explosion. Spalling has stopped
56:00	Test is terminated

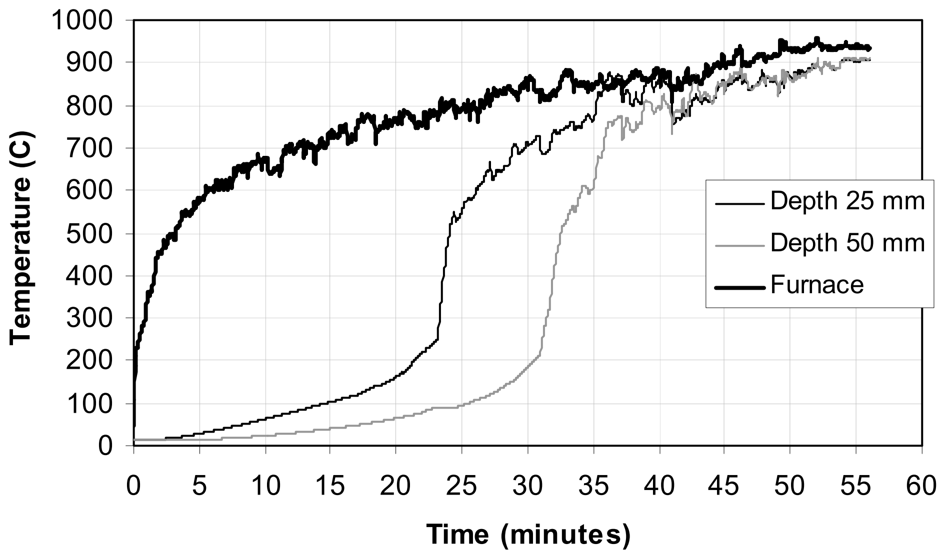

Figure B81. Furnace temperature and temperatures in specimen SS 55 04. The specimen was loaded in compression during the test.

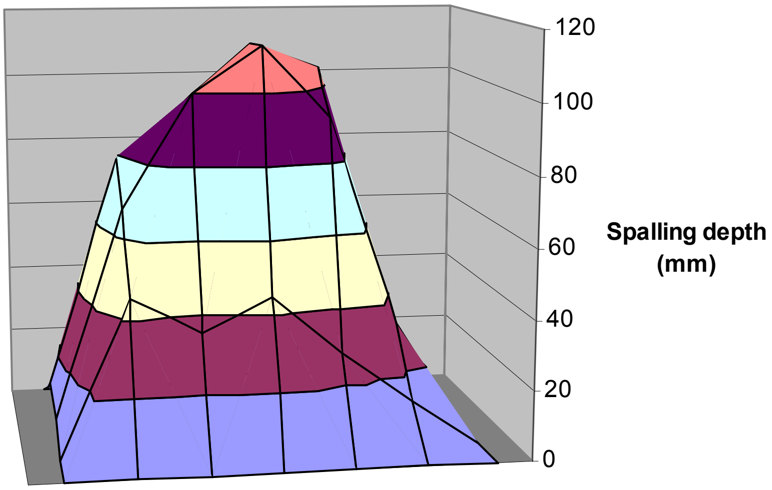

Figure B82. Spalling depth of specimen SS 55 04.

Table B38. Spalling depth of specimen SS 55 04. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	25	115	205	295	385	475
30	0	0	7	12	6	0
120	0	46	68	79	28	0
210	0	35	100	95	42	0
300	0	45	113	112	30	2
390	0	28	93	105	30	3
480	0	13	31	33	3	0
570	0	0	0	0	0	0

Appendix C –Measurements on tunnel concrete

C1 – Thermocouple numbering

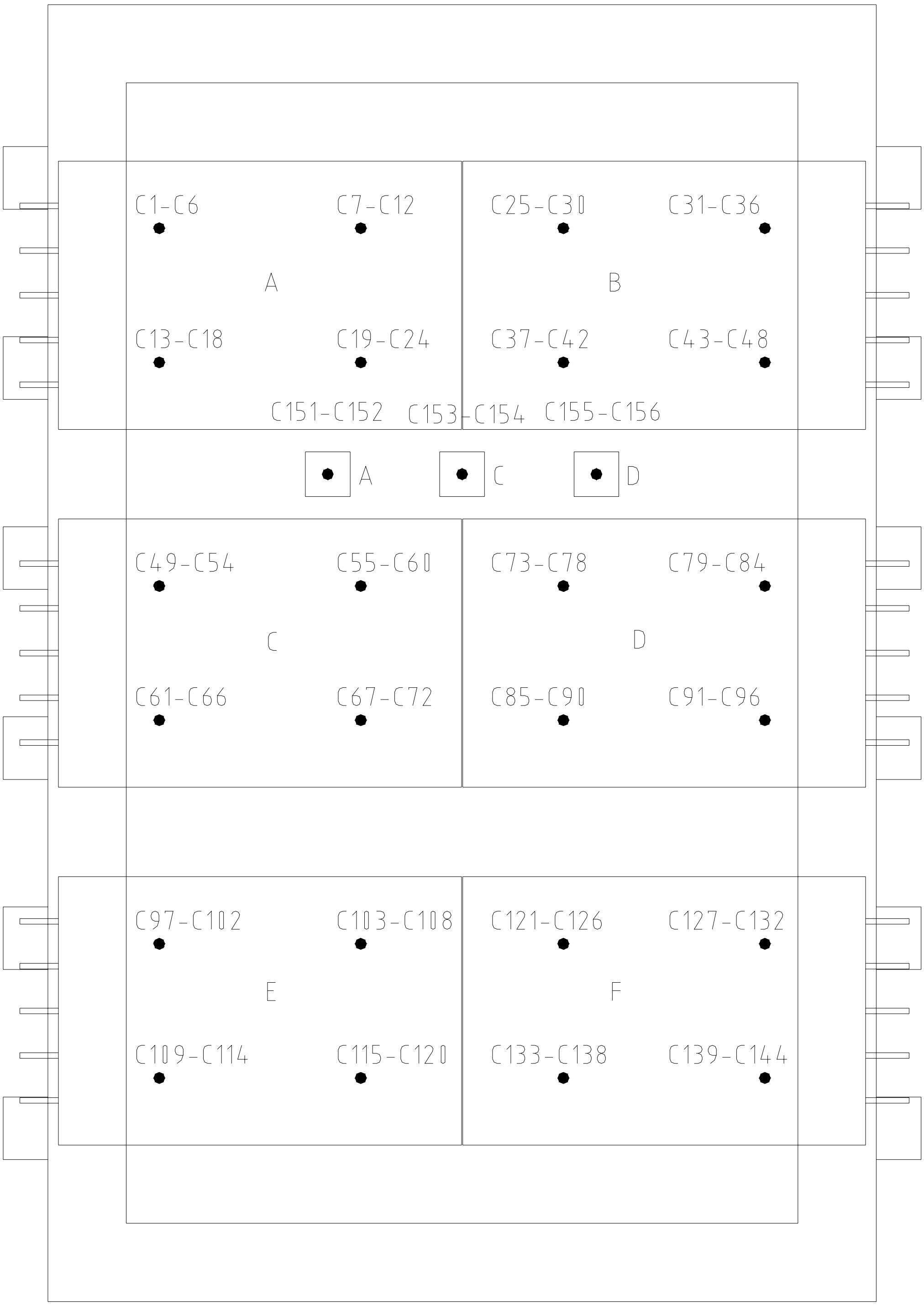

Figure C1. Position of thermocouples.

C2 – Measurements on specimen A1

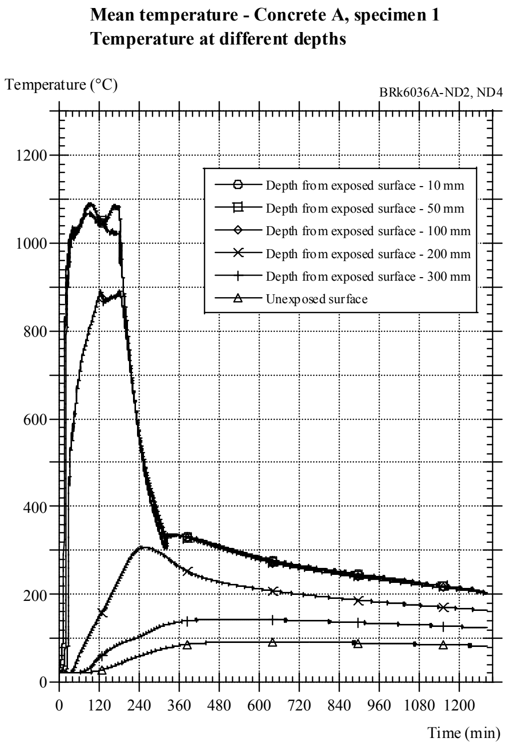

Figure C2. Mean temperatures.

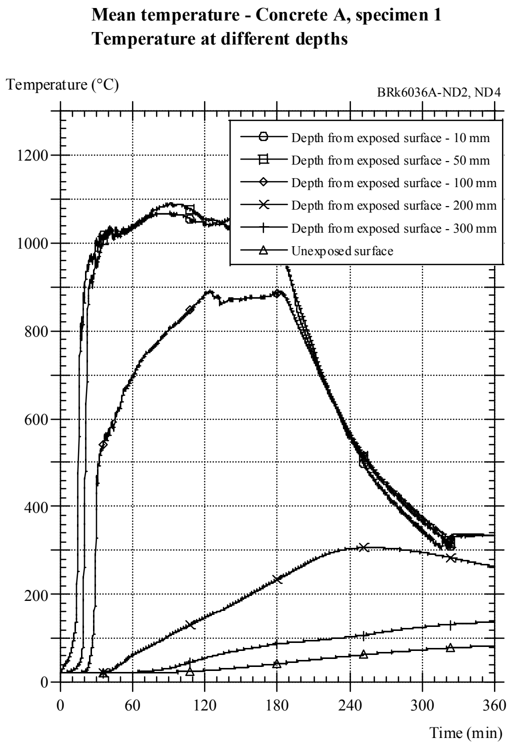

Figure C3. Mean temperatures.

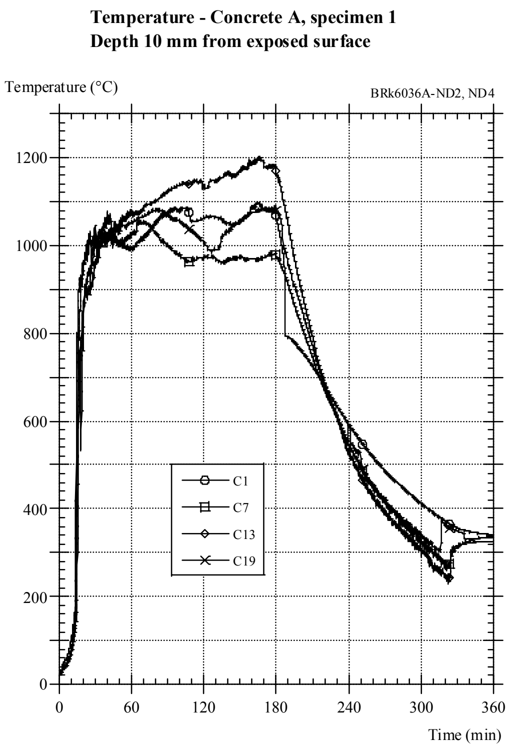

Figure C4. Temperatures 10 mm from the exposed surface.

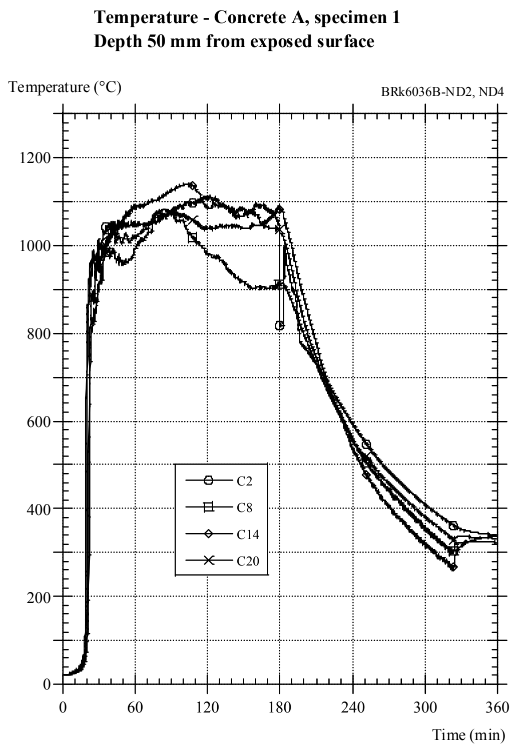

Figure C5. Temperatures 50 mm from the exposed surface.

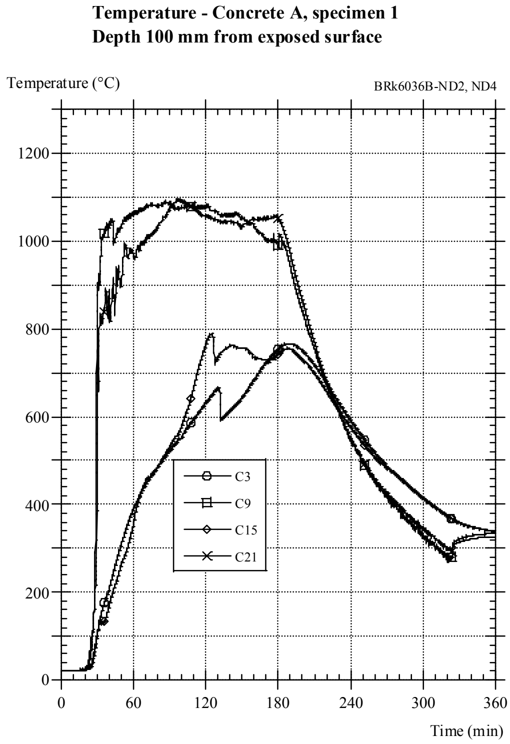

Figure C6. Temperatures 100 mm from the exposed surface.

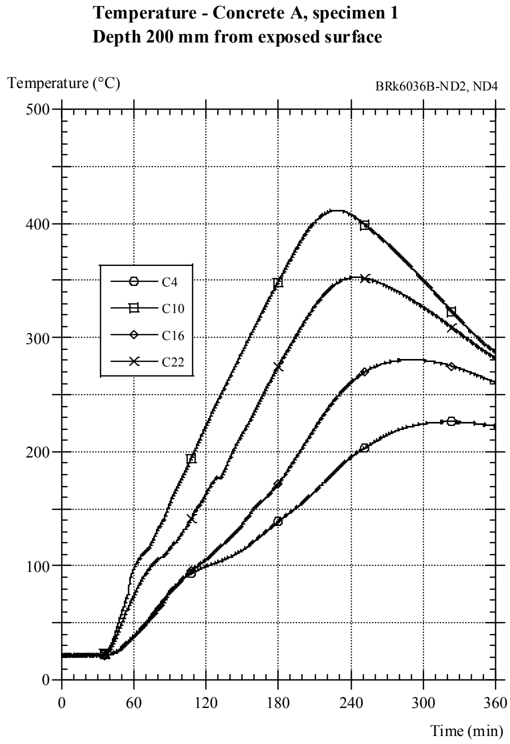

Figure C7. Temperatures 200 mm from the exposed surface.

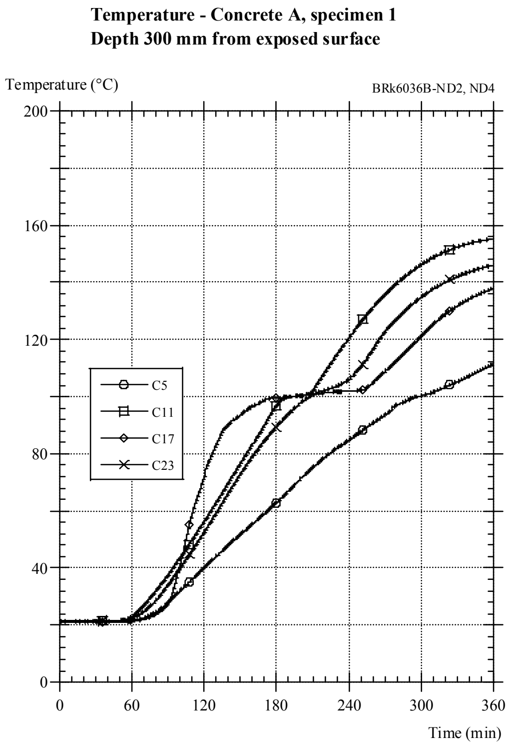

Figure C8. Temperatures 300 mm from the exposed surface.

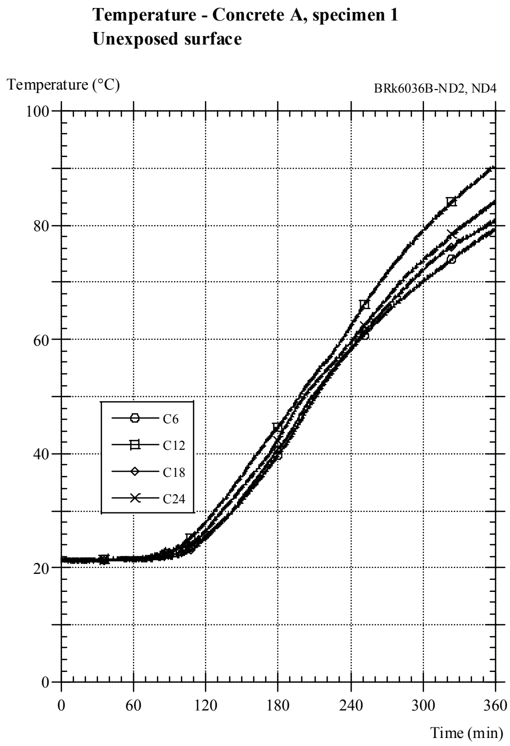

Figure C9. Temperatures on the unexposed surface.

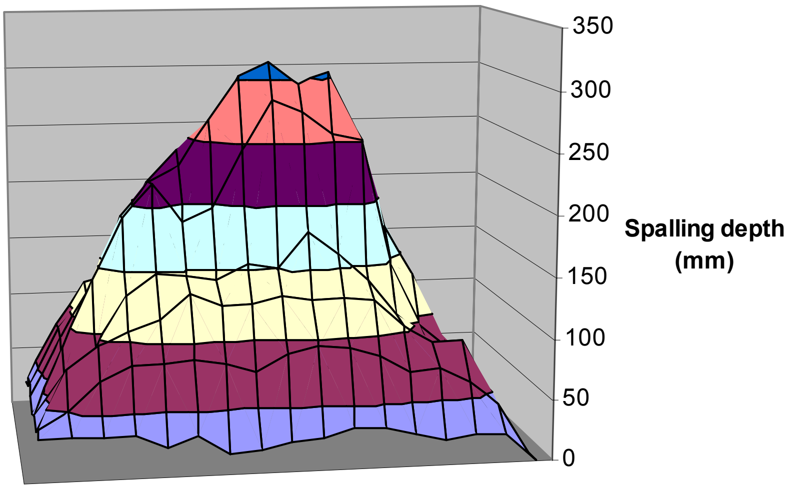

Figure C10. Spalling depth of specimen A1.

Table C1. Spalling depth of specimen A1. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	36	36	28	34	28	23	31	36	36	21	18
200	35	51	78	68	84	59	82	85	83	67	24
300	34	74	96	90	140	103	122	112	118	74	24
400	35	85	107	131	191	188	163	146	126	117	28
500	25	86	116	149	218	216	213	187	134	116	32
600	33	87	136	147	186	230	239	187	148	109	32
700	18	83	126	143	198	266	251	194	143	100	37
800	18	76	127	154	244	304	263	202	129	82	28
900	25	89	133	150	285	314	263	186	113	72	36
1000	26	96	128	179	276	296	258	190	111	70	42
1100	34	94	129	161	257	306	269	181	101	74	28
1200	33	86	127	139	251	256	207	153	89	73	21
1300	26	72	103	109	146	174	181	131	93	74	26
1400	21	73	90	85	94	132	114	92	77	66	31
1500	24	61	90	63	72	65	74	81	76	58	23
1600	24	41	42	48	35	46	51	42	32	29	10
1700	0	0	0	0	1	1	1	1	1	1	1

C3 – Measurements on specimen A2

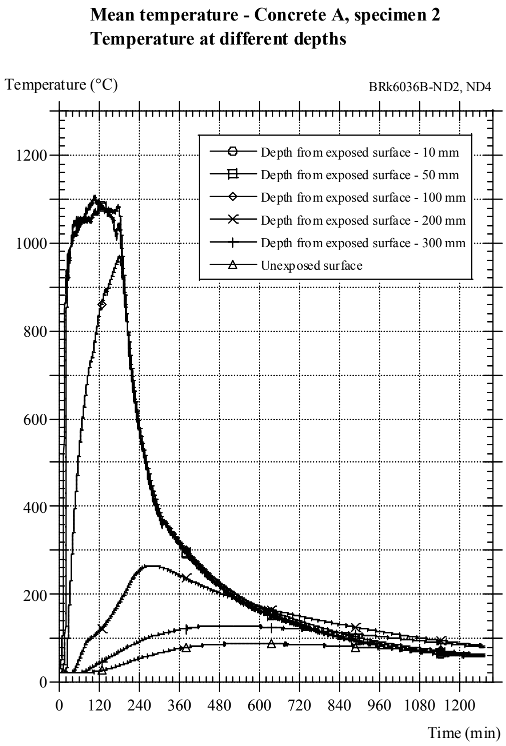

Figure C11. Mean temperatures.

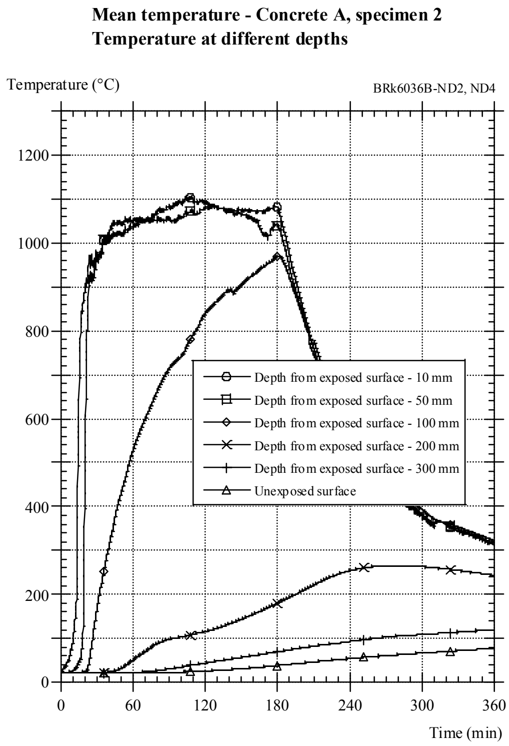

Figure C12. Mean temperatures.

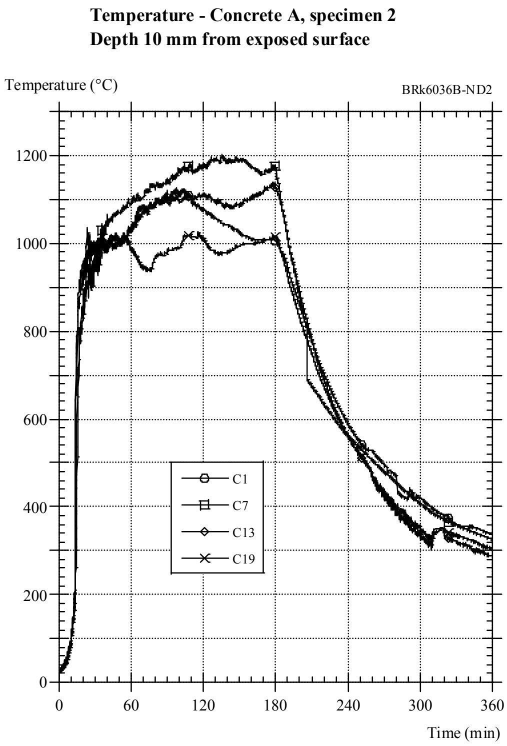

Figure C13. Temperatures 10 mm from the exposed surface.

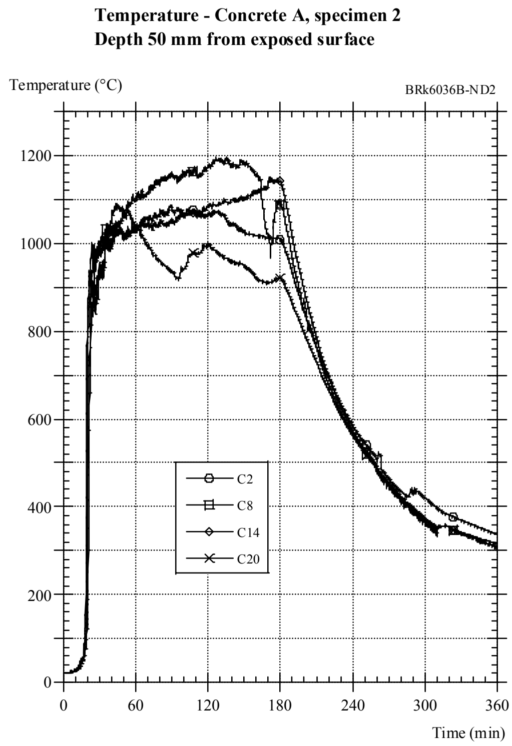

Figure C14. Temperatures 50 mm from the exposed surface.

Temperature - Concrete A, specimen 2
Depth 100 mm from exposed surface

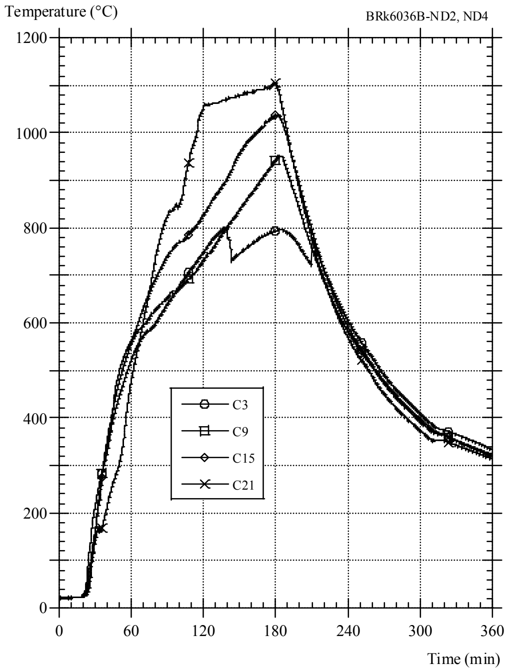

Figure C15. Temperatures 100 mm from the exposed surface.

Temperature - Concrete A, specimen 2
Depth 200 mm from exposed surface

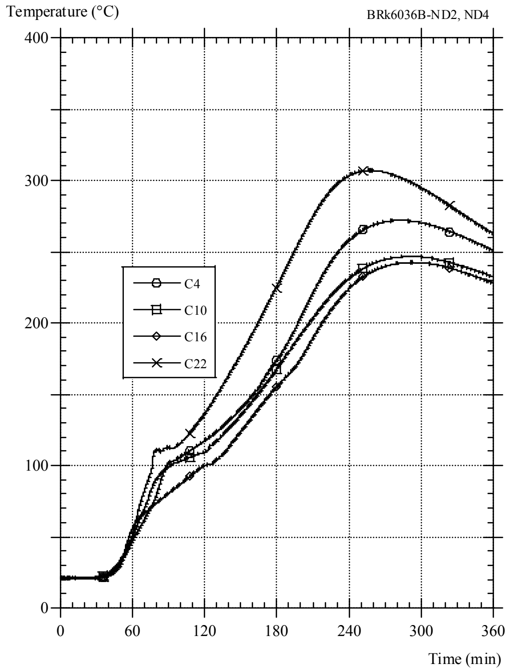

Figure C16. Temperatures 200 mm from the exposed surface.

Temperature - Concrete A, specimen 2
Depth 300 mm from exposed surface

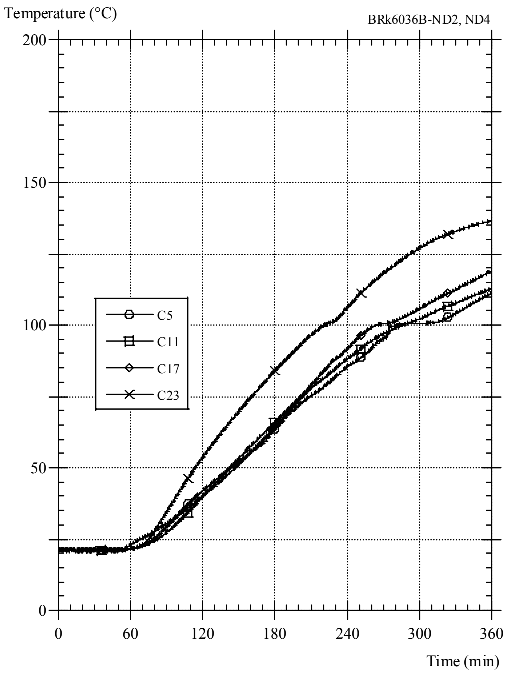

Figure C17. Temperatures 300 mm from the exposed surface.

Temperature - Concrete A, specimen 2
Unexposed surface

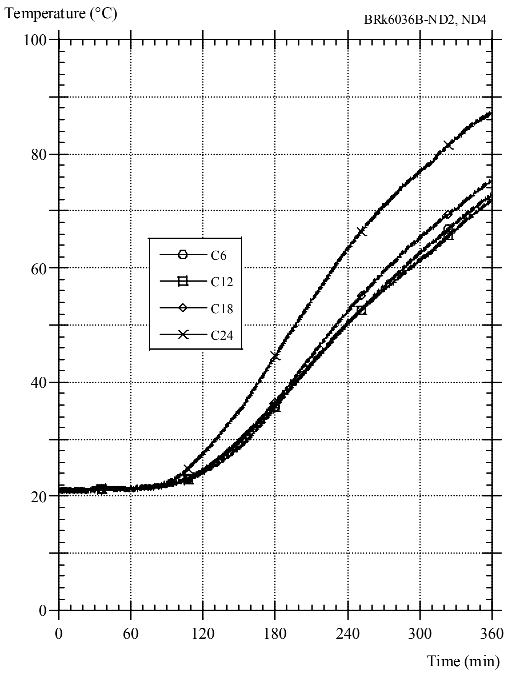

Figure C18. Temperatures on the unexposed surface.

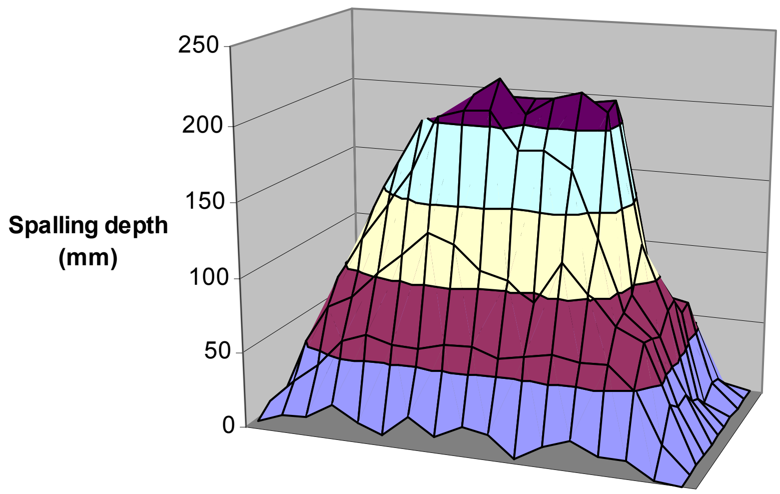

Figure C19. Spalling depth of specimen A2.

Table C2. Spalling depth of specimen A2. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	5	12	8	5	3	11	2	2	16	7	12
200	11	29	47	51	50	48	55	49	50	38	11
300	12	42	76	91	97	79	88	73	75	69	21
400	22	60	84	119	137	115	131	90	85	66	15
500	12	66	103	143	167	134	147	100	77	63	17
600	7	62	116	168	197	144	115	92	74	61	20
700	21	61	133	204	96	137	106	101	74	60	17
800	10	66	126	209	216	211	125	97	67	50	16
900	20	66	111	210	227	213	121	96	64	49	17
1000	17	61	106	186	206	212	138	89	64	51	10
1100	3	64	94	187	217	214	172	143	76	59	18
1200	13	67	121	176	222	213	209	137	82	53	17
1300	19	64	103	134	210	215	189	119	78	43	15
1400	12	65	84	88	95	123	107	82	74	52	12
1500	12	51	75	73	69	81	82	68	70	52	17
1600	1	17	37	30	32	21	16	8	15	13	3
1700	0	0	0	0	0	0	0	0	0	0	0

C4 – Temperatures in columns A10 and A11

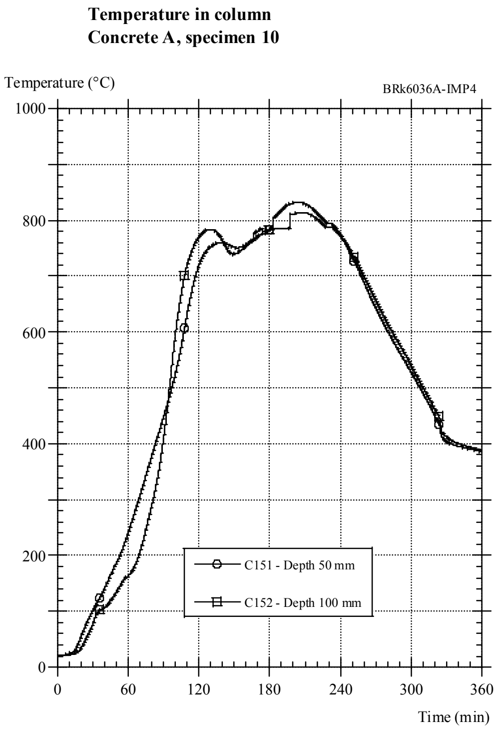

Figure C20. Temperatures at different depths of column A 10.

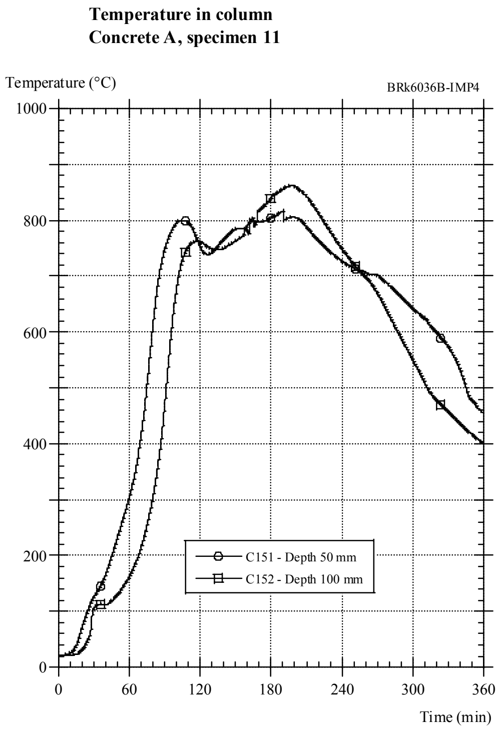

Figure C21. Temperatures at different depths of column A 11.

C5 – Measurements on specimen B1

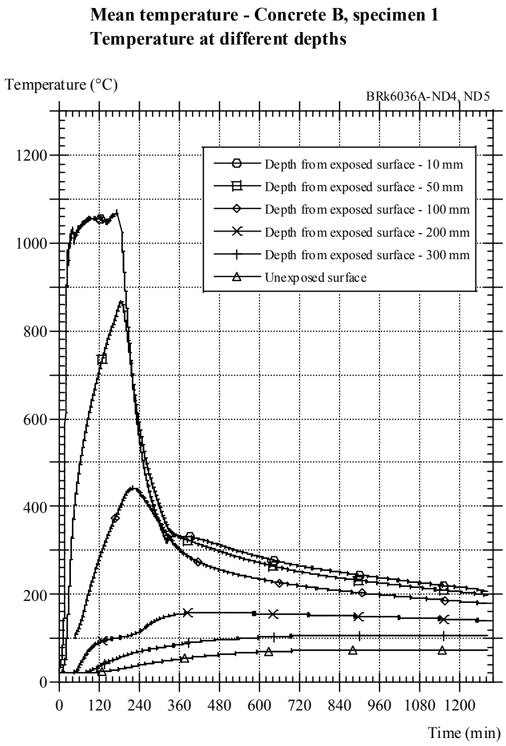

Figure C22. Mean temperatures.

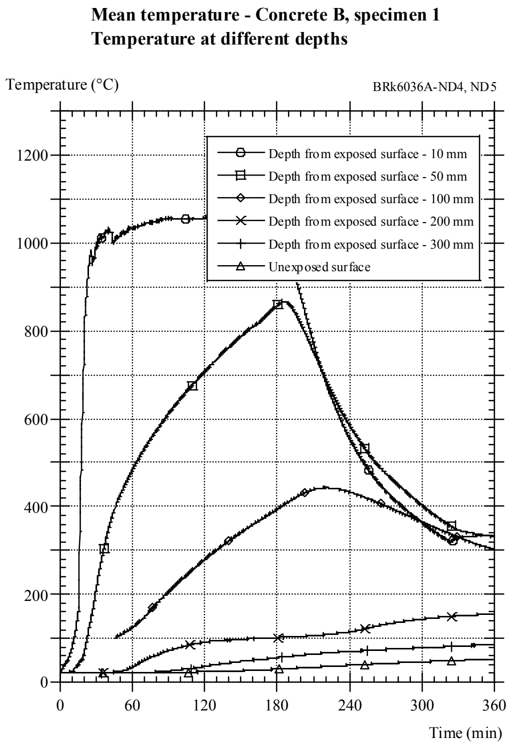

Figure C23. Mean temperatures.

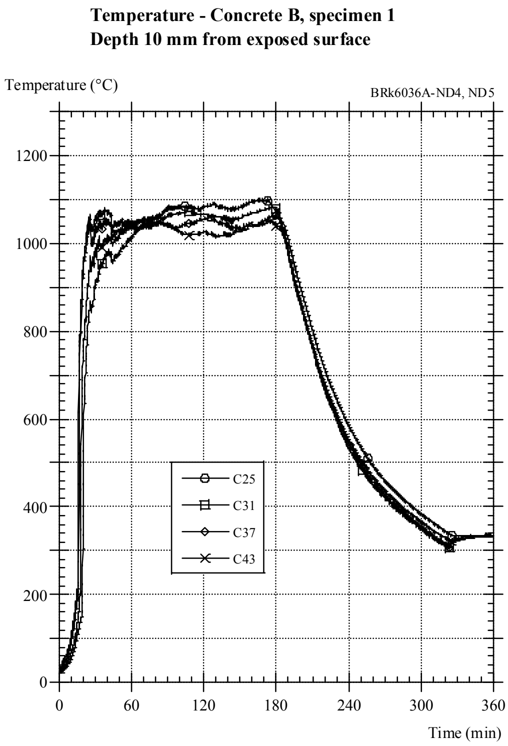

Figure C24. Temperatures 10 mm from the exposed surface.

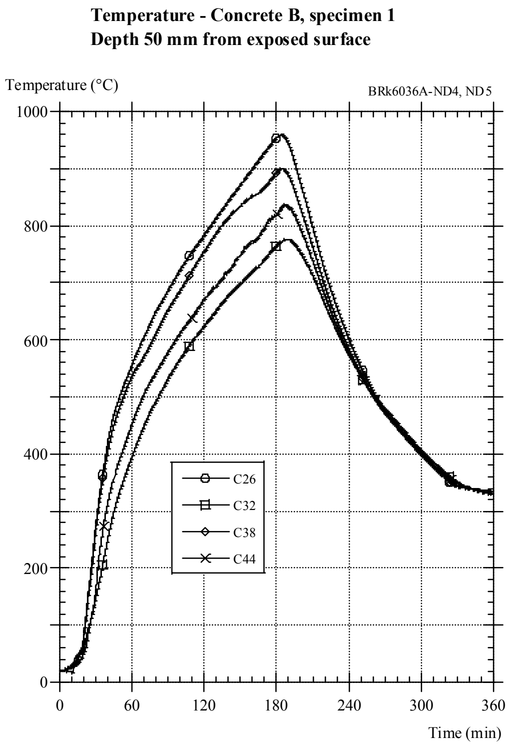

Figure C25. Temperatures 50 mm from the exposed surface.

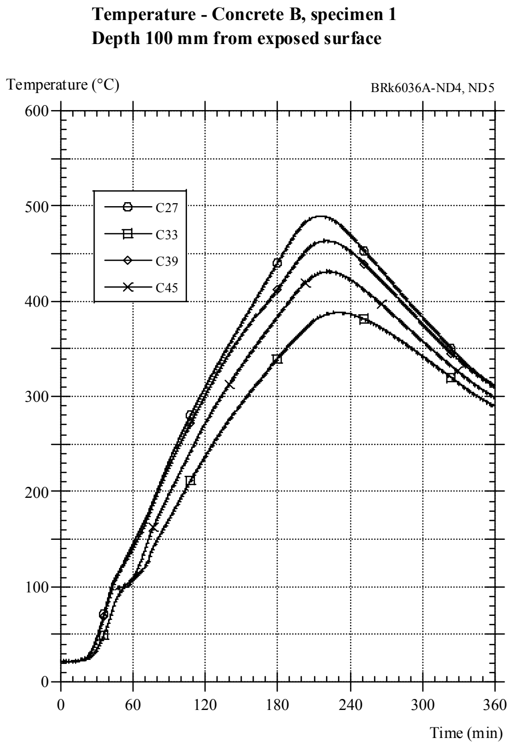

Figure C26. Temperatures 100 mm from the exposed surface.

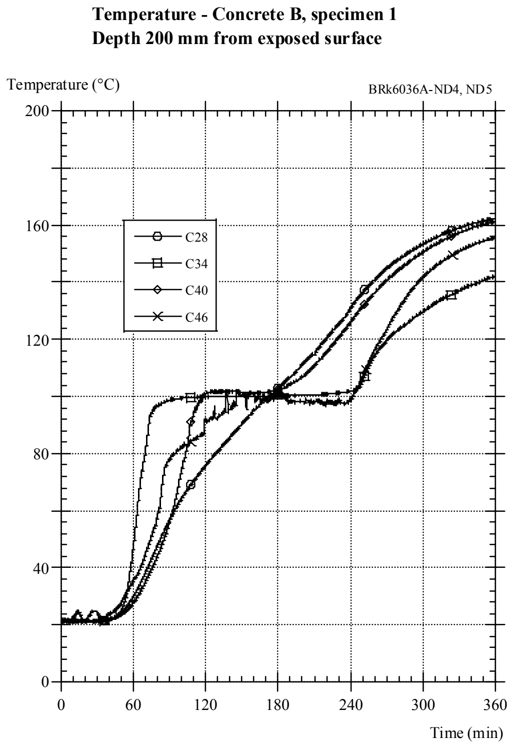

Figure C27. Temperatures 200 mm from the exposed surface.

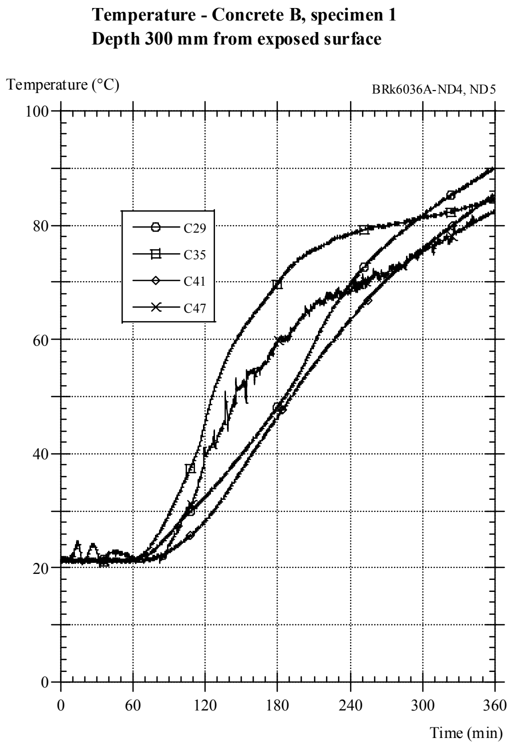

Figure C28. Temperatures 300 mm from the exposed surface.

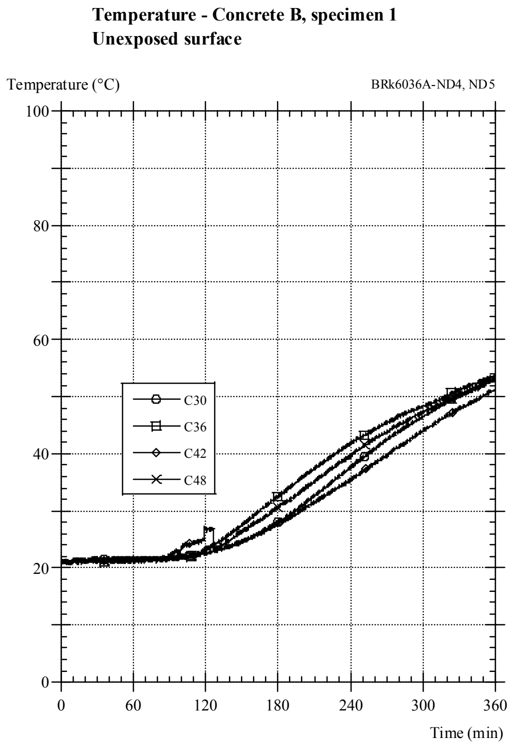

Figure C29. Temperatures on the unexposed surface.

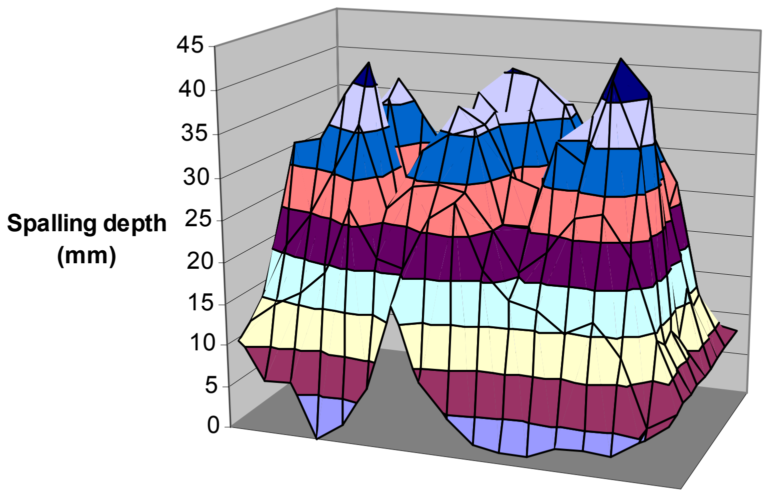

Figure C30. Spalling depth of specimen B1.

Table C3. Spalling depth of specimen B1. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	11	12	14	20	13	13	13	14	13	13	13
200	6	15	21	33	23	13	21	30	18	15	13
300	6	16	25	33	28	15	27	33	28	18	12
400	0	19	31	39	30	19	21	36	38	25	22
500	2	27	36	43	35	14	16	21	33	29	20
600	7	21	27	27	27	14	15	12	28	27	3
700	17	21	29	33	27	24	21	23	33	22	3
800	8	27	30	35	37	35	38	37	29	11	2
900	5	29	29	36	36	37	35	41	32	20	2
1000	2	21	25	25	30	27	36	40	28	12	3
1100	1	18	20	25	29	25	27	37	36	20	4
1200	1	17	23	35	25	23	26	30	30	22	3
1300	3	15	27	33	38	30	26	31	31	21	3
1400	3	17	28	42	44	41	29	30	34	31	4
1500	3	13	23	34	41	34	30	25	28	15	6
1600	5	5	14	13	13	12	17	14	14	8	9
1700	7	7	7	7	7	7	7	7	8	8	8

C6 – Measurements on specimen B2

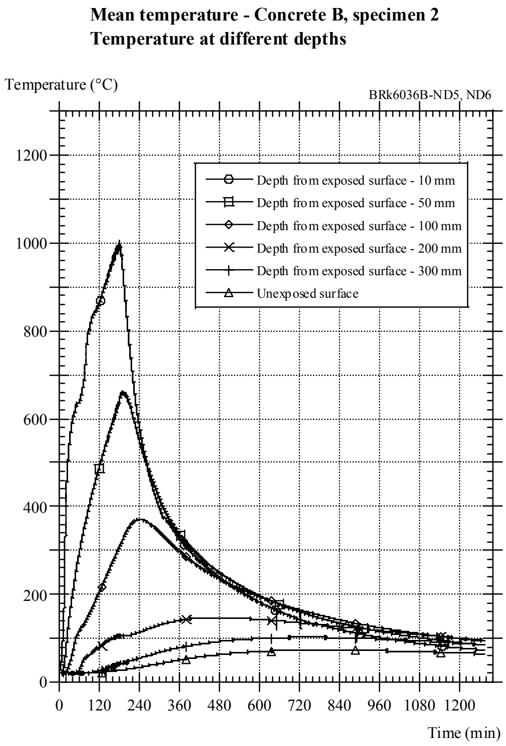

Figure C31. Mean temperatures.

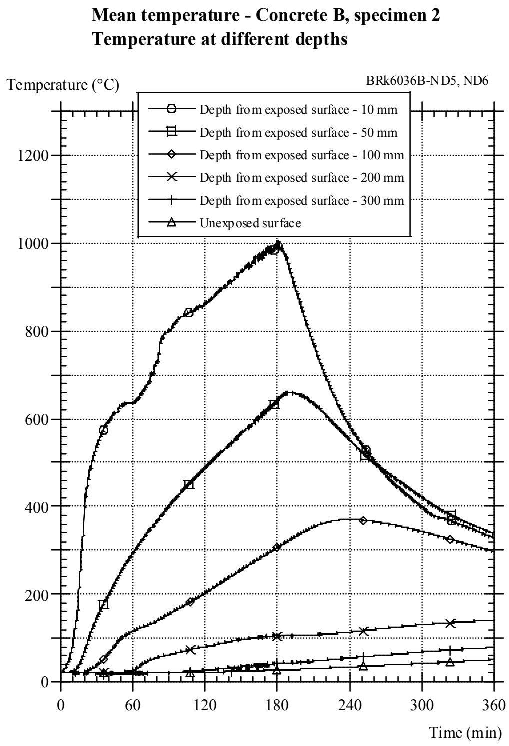

Figure C32. Mean temperatures.

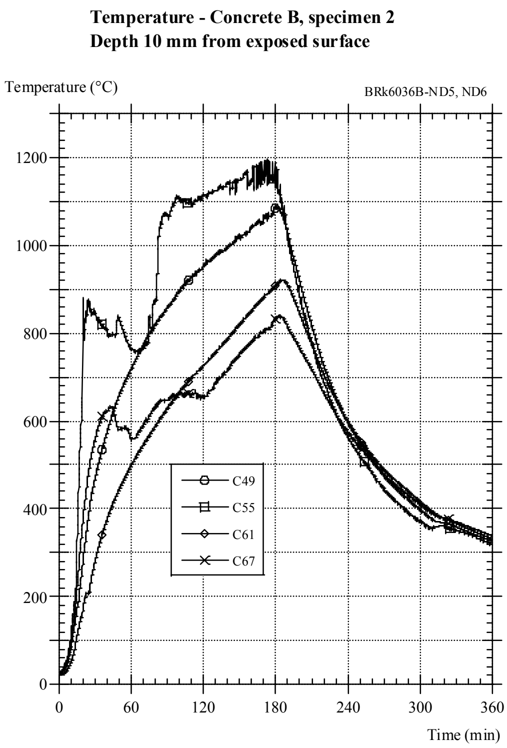

Figure C33. Temperatures 10 mm from the exposed surface.

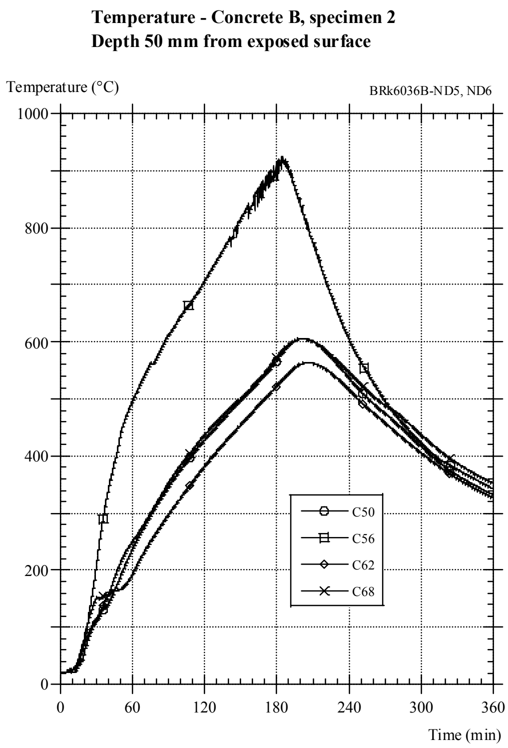

Figure C34. Temperatures 50 mm from the exposed surface.

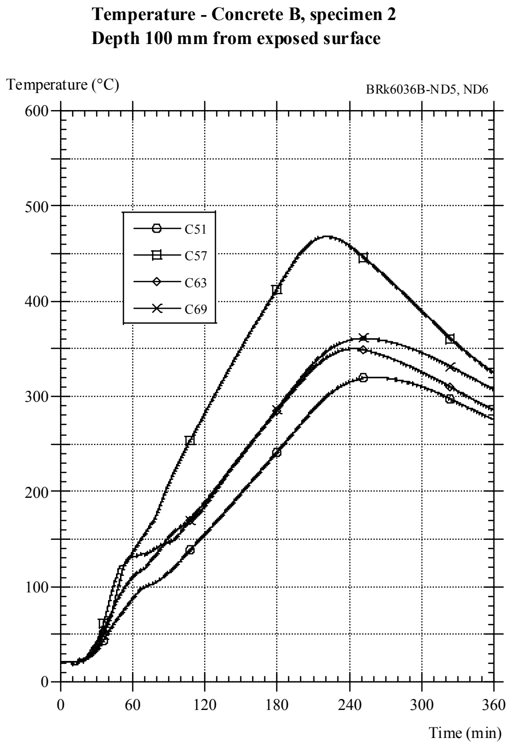

Figure C35. Temperatures 100 mm from the exposed surface.

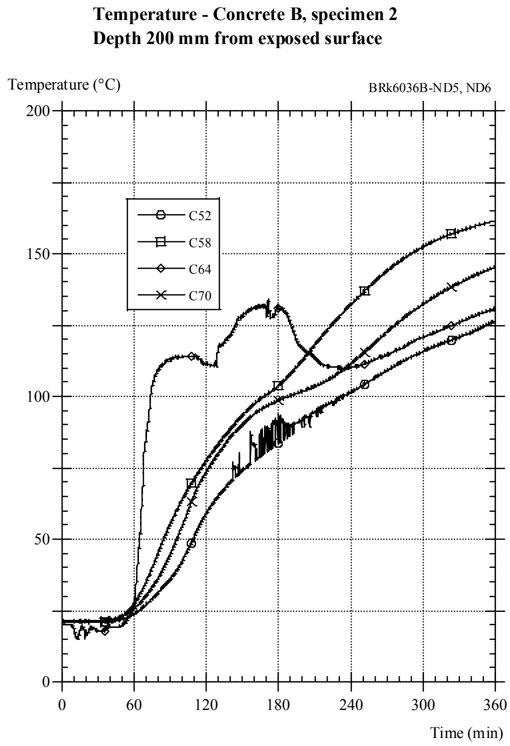

Figure C36. Temperatures 200 mm from the exposed surface.

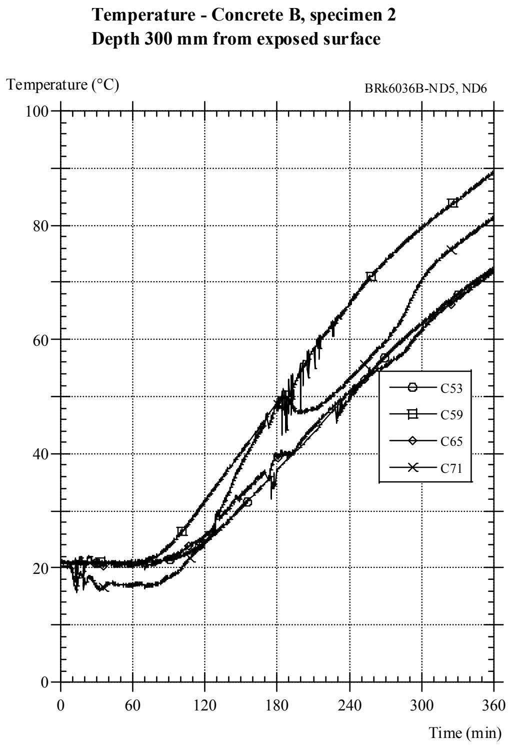

Figure C37. Temperatures 300 mm from the exposed surface.

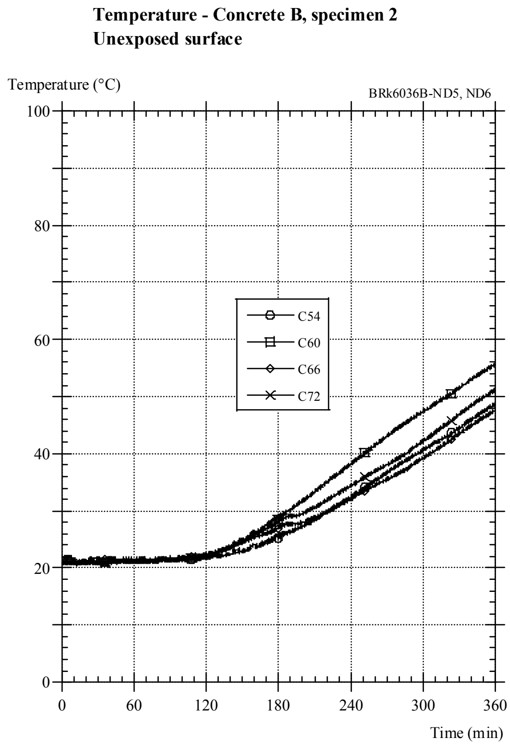

Figure C38. Temperatures on the unexposed surface.

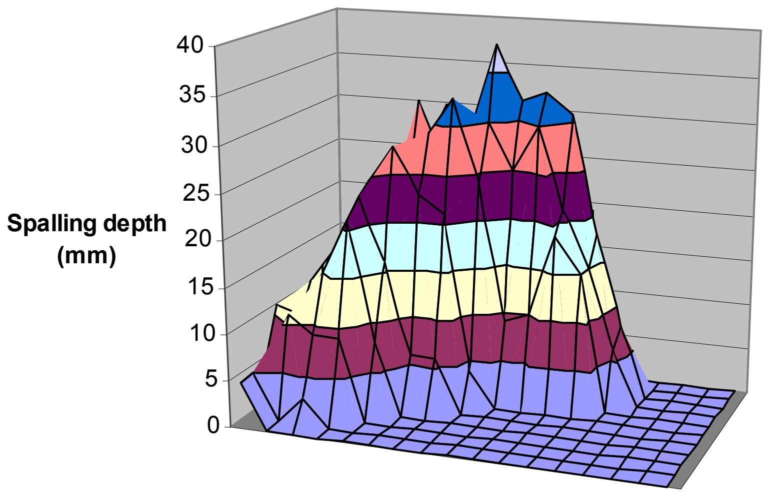

Figure C39. Spalling depth of specimen B2.

Table C4. Spalling depth of specimen B2. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	5	5	5	11	7	10	6	8	7	14	12
200	0	0	11	10	13	12	10	16	15	18	3
300	0	3	9	15	17	15	12	16	23	19	5
400	0	0	9	21	23	24	13	23	25	23	30
500	0	0	0	8	16	28	11	22	26	26	23
600	0	0	0	0	6	23	29	24	31	18	8
700	0	0	0	0	6	21	33	26	29	26	7
800	0	0	0	0	0	4	24	30	38	21	0
900	0	0	0	0	0	0	9	25	32	22	0
1000	0	0	0	0	0	0	10	30	33	26	5
1100	0	0	0	0	0	0	19	21	31	18	5
1200	0	0	0	0	0	0	15	15	18	13	0
1300	0	0	0	0	0	0	0	6	8	0	0
1400	0	0	0	0	0	0	0	0	0	0	0
1500	0	0	0	0	0	0	0	0	0	0	0
1600	0	0	0	0	0	0	0	0	0	0	0
1700	0	0	0	0	0	0	0	0	0	0	0

C7 – Measurements on specimen C1

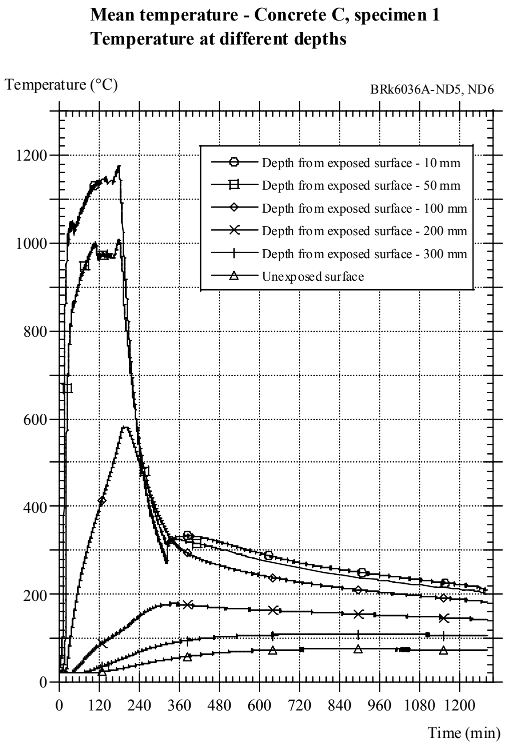

Figure C40. Mean temperatures.

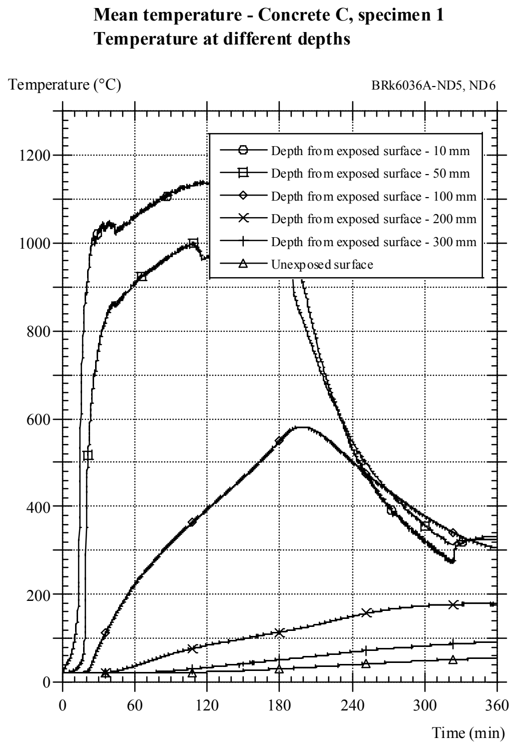

Figure C41. Mean temperatures.

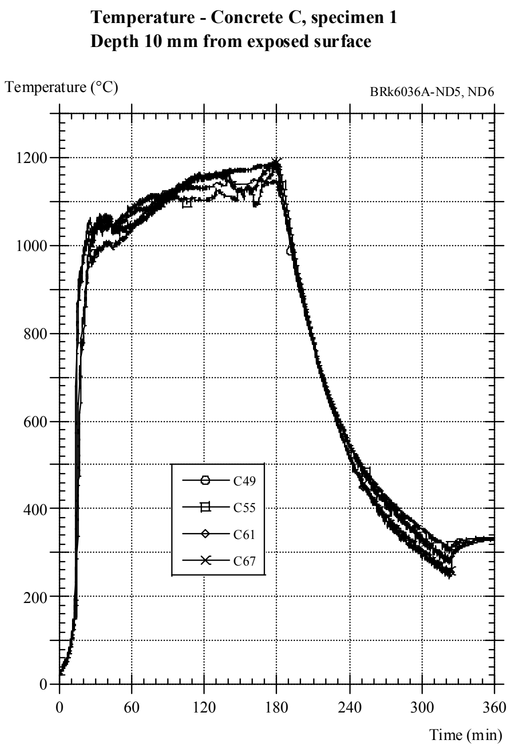

Figure C42. Temperatures 10 mm from the exposed surface.

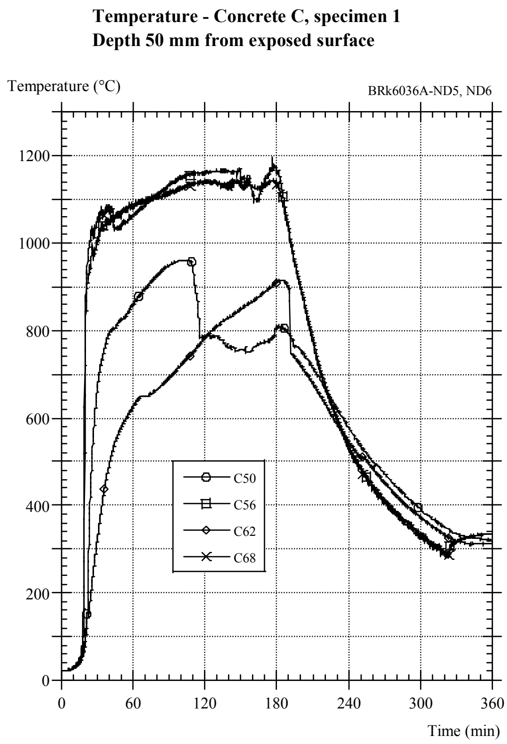

Figure C43. Temperatures 50 mm from the exposed surface.

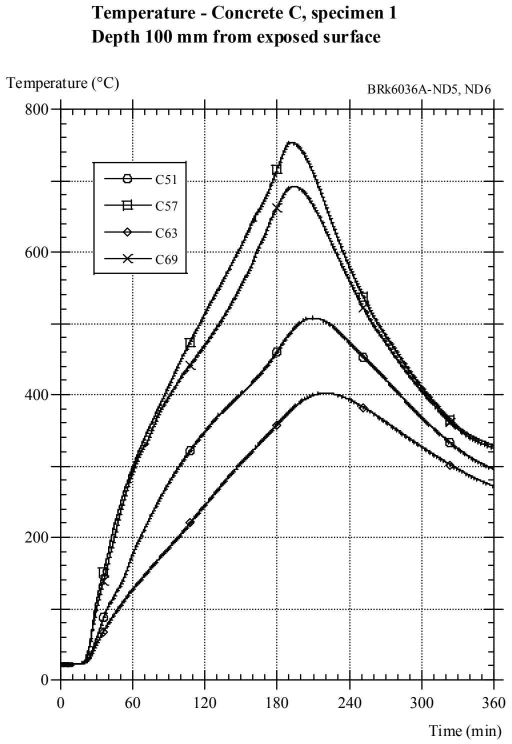

Figure C44. Temperatures 100 mm from the exposed surface.

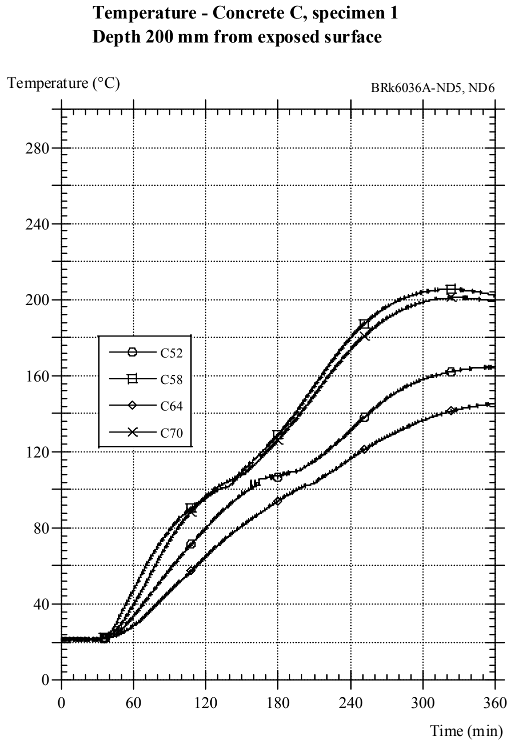

Figure C45. Temperatures 200 mm from the exposed surface.

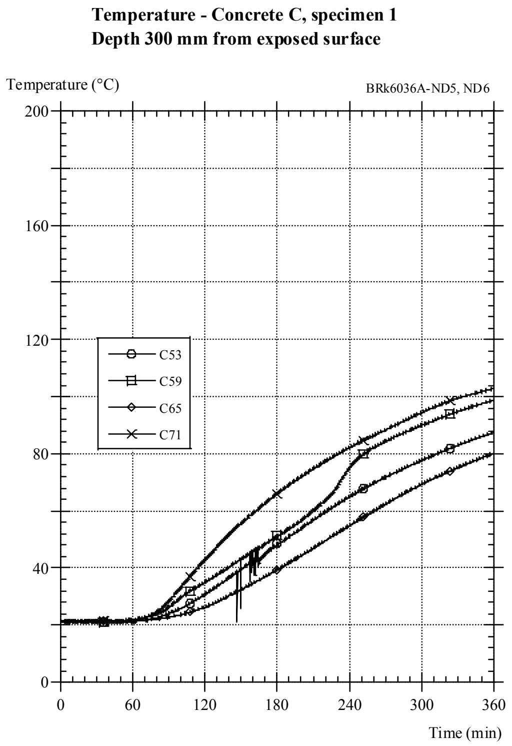

Figure C46. Temperatures 300 mm from the exposed surface.

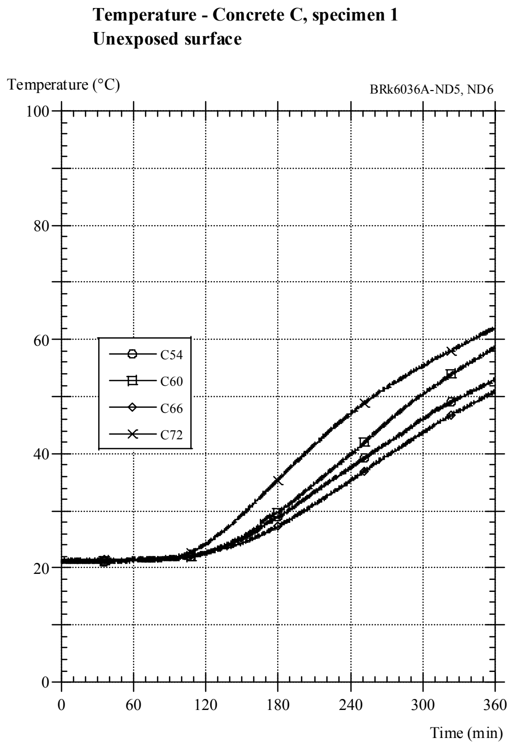

Figure C47. Temperatures on the unexposed surface.

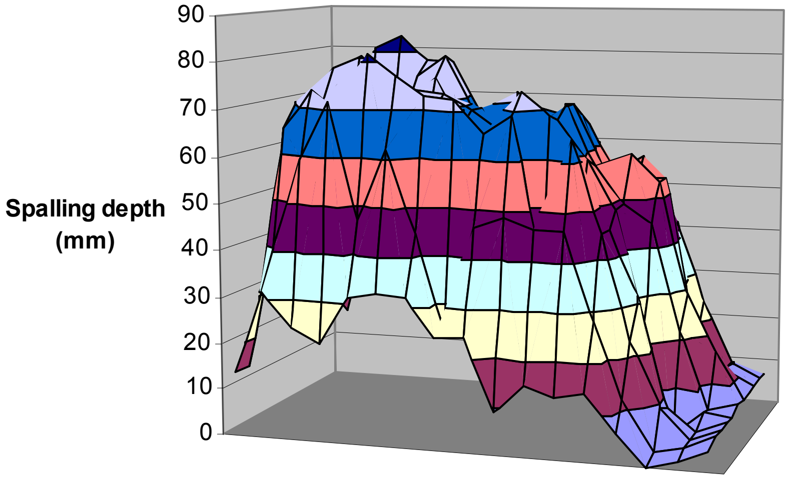

Figure C48. Spalling depth of specimen C1.

Table C5. Spalling depth of specimen C1. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	14	14	27	34	37	38	41	30	18	20	16
200	32	41	65	70	70	70	73	66	39	35	35
300	24	59	74	71	78	65	64	56	81	55	23
400	21	72	68	66	80	61	67	59	84	55	23
500	31	47	82	70	77	71	70	75	78	60	26
600	32	62	77	69	73	62	75	80	78	46	24
700	32	45	73	70	73	67	64	68	66	49	34
800	24	23	73	67	69	69	64	64	67	49	27
900	24	46	65	63	65	57	72	51	68	54	25
1000	9	49	70	74	61	61	66	59	66	55	13
1100	15	47	38	69	67	70	70	67	64	49	18
1200	13	46	65	47	59	57	57	51	54	51	20
1300	14	28	45	45	49	49	59	53	58	46	10
1400	7	12	23	31	24	45	53	54	39	42	12
1500	0	2	9	8	1	22	29	20	19	24	10
1600	2	3	3	3	6	5	17	7	10	10	5
1700	4	6	6	6	5	7	6	6	7	7	7

C8 – Measurements on specimen C2

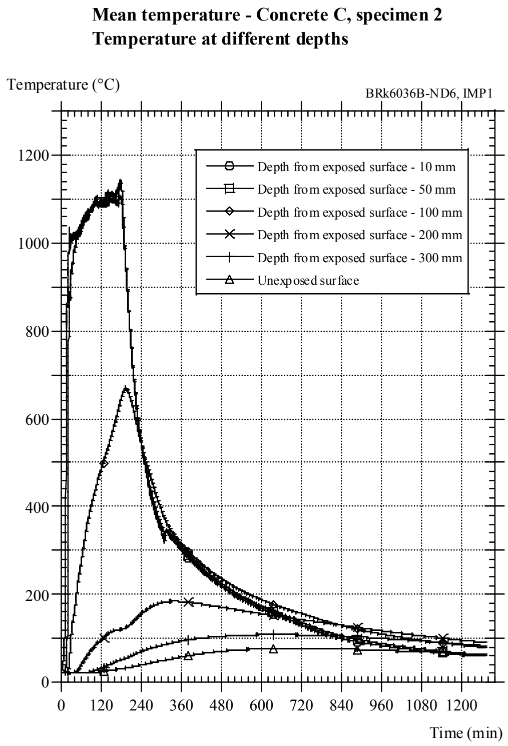

Figure C49. Mean temperatures.

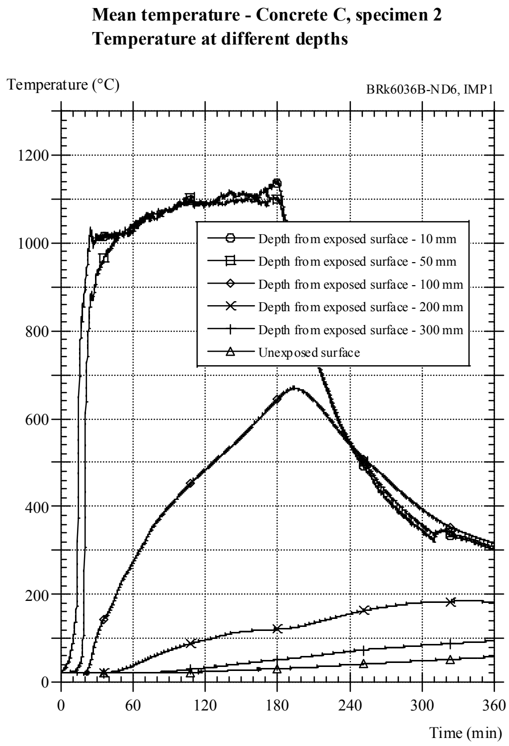

Figure C50. Mean temperatures.

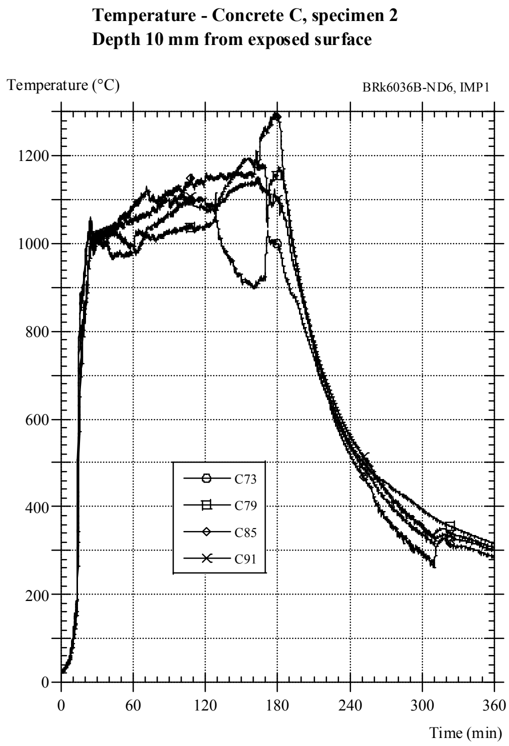

Figure C51. Temperatures 10 mm from the exposed surface.

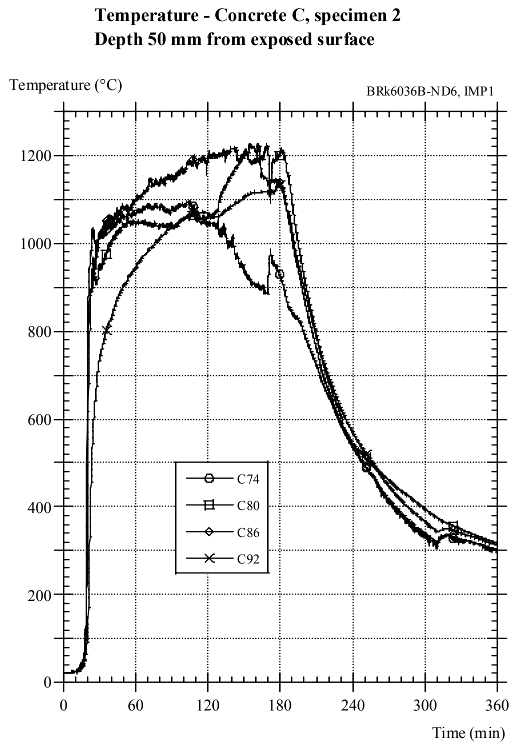

Figure C52. Temperatures 50 mm from the exposed surface.

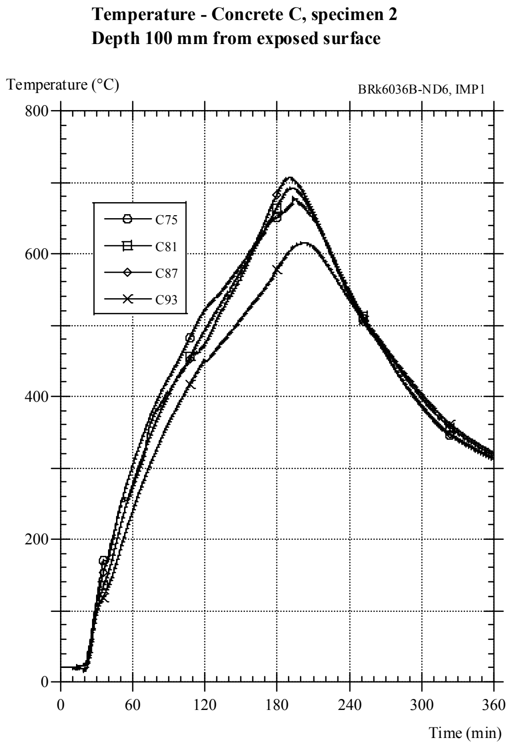

Figure C53. Temperatures 100 mm from the exposed surface.

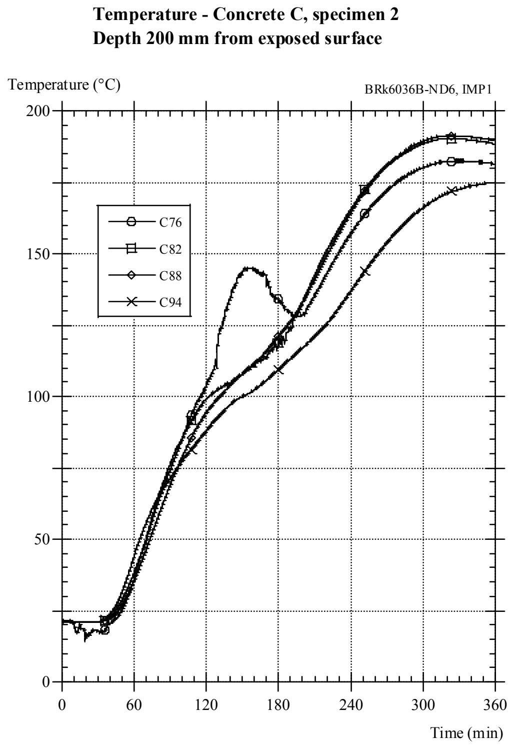

Figure C54. Temperatures 200 mm from the exposed surface.

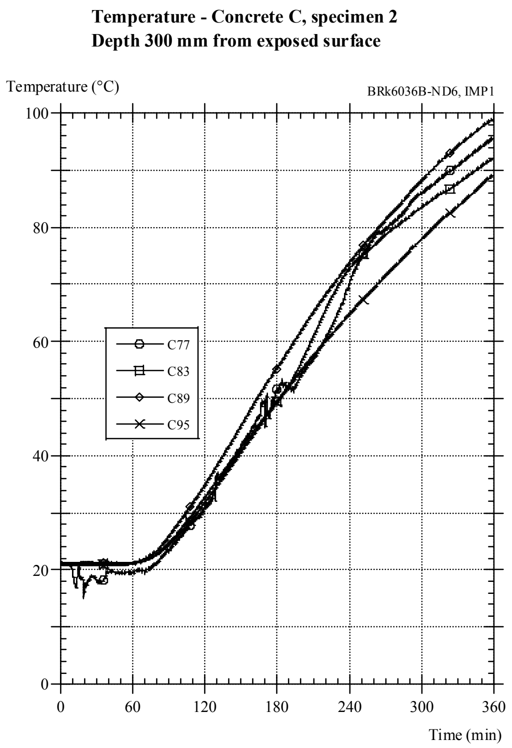

Figure C55. Temperatures 300 mm from the exposed surface.

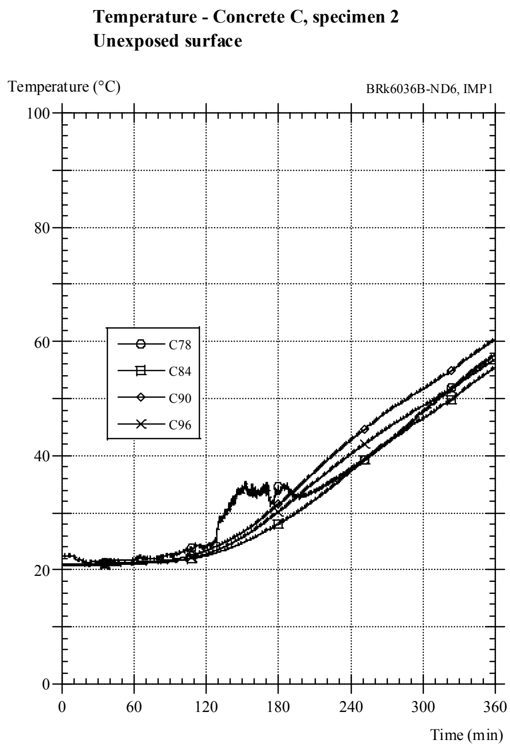

Figure C56. Temperatures on the unexposed surface.

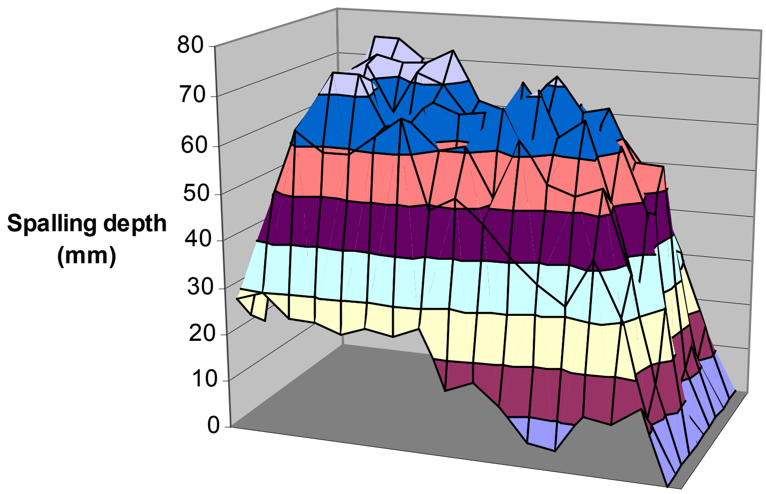

Figure C57. Spalling depth of specimen C2.

Table C6. Spalling depth of specimen C2. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	28	23	20	46	42	24	31	29	42	23	9
200	30	49	54	55	52	55	56	60	56	33	16
300	25	63	65	66	71	65	71	67	76	38	20
400	25	59	74	61	65	73	74	71	76	50	12
500	23	59	74	72	55	63	73	67	72	58	21
600	25	63	64	49	60	72	73	70	59	50	20
700	24	67	65	67	67	70	76	44	61	54	16
800	26	49	60	47	65	63	66	58	55	47	14
900	14	52	61	56	66	53	64	42	68	50	21
1000	16	47	51	68	65	57	66	55	61	48	25
1100	12	41	63	58	71	64	72	58	61	63	21
1200	5	36	55	63	59	44	65	45	60	42	18
1300	4	32	53	67	55	64	66	56	57	41	2
1400	12	42	55	51	61	51	55	48	50	45	3
1500	11	31	38	32	48	46	55	36	34	32	3
1600	15	11	16	30	10	7	12	15	10	16	4
1700	0	0	0	0	0	0	0	0	0	0	0

C9 – Temperatures in columns C10 and C11

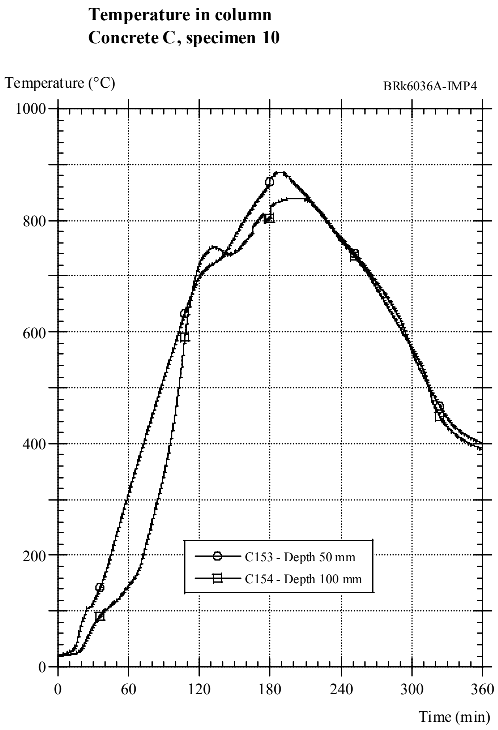

Figure C58. Temperatures at different depths of column C 10.

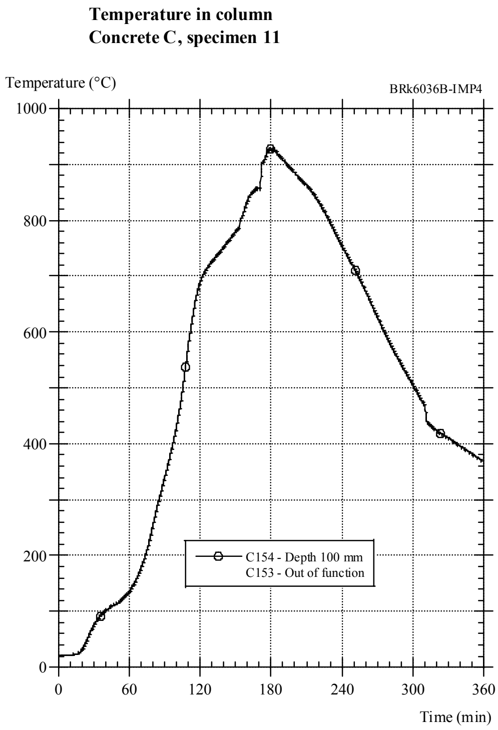

Figure C59. Temperatures at different depths of column C 11.

C10 – Measurements on specimen D1

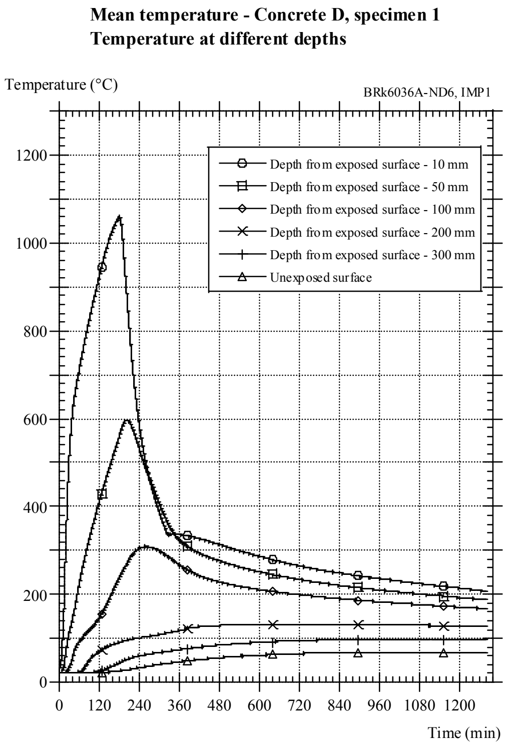

Figure C60. Mean temperatures.

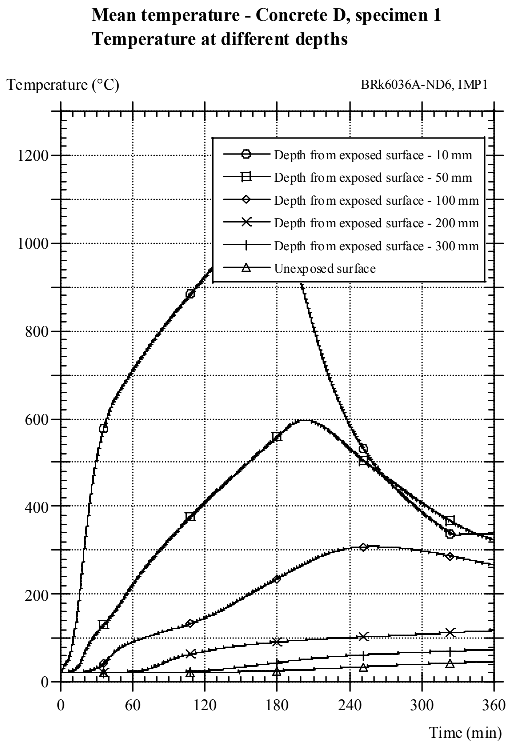

Figure C61. Mean temperatures.

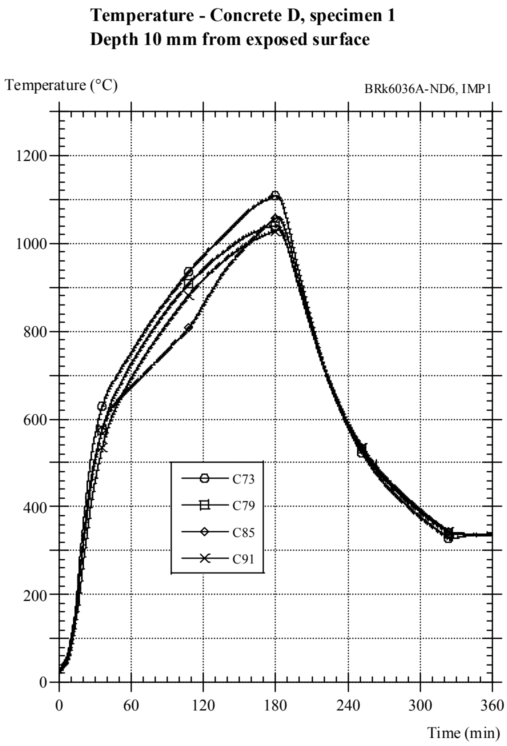

Figure C62. Temperatures 10 mm from the exposed surface.

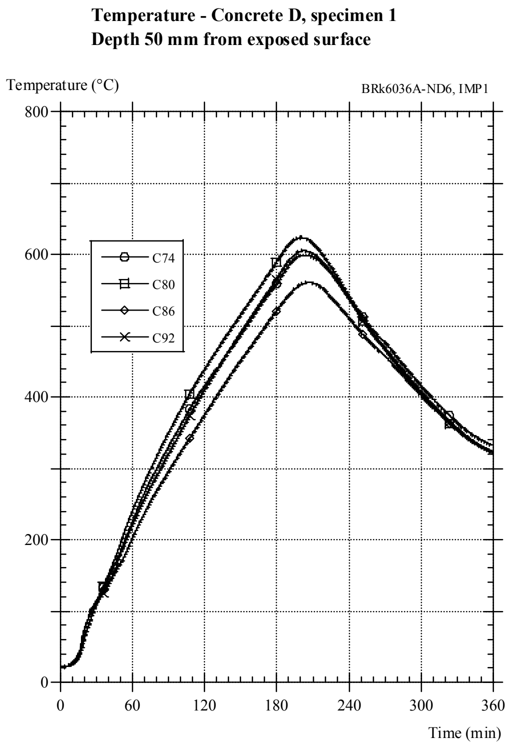

Figure C63. Temperatures 50 mm from the exposed surface.

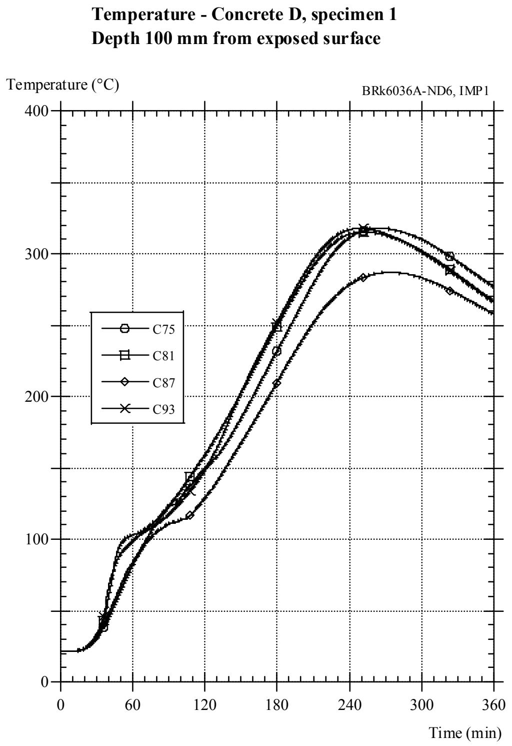

Figure C64. Temperatures 100 mm from the exposed surface.

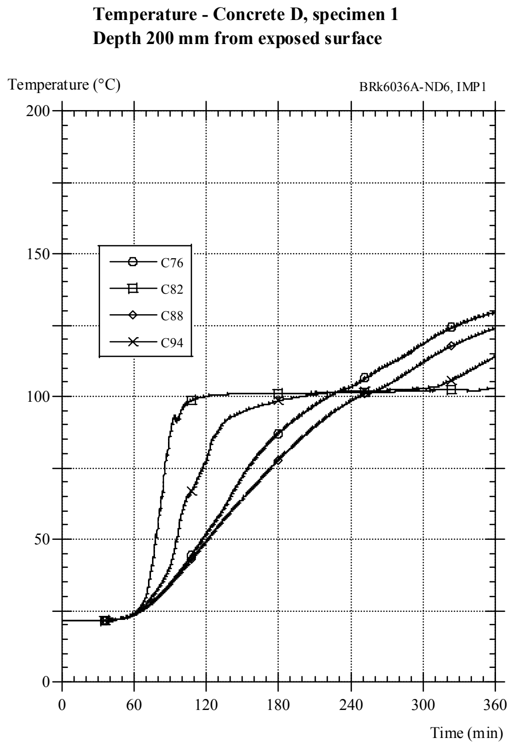

Figure C65. Temperatures 200 mm from the exposed surface.

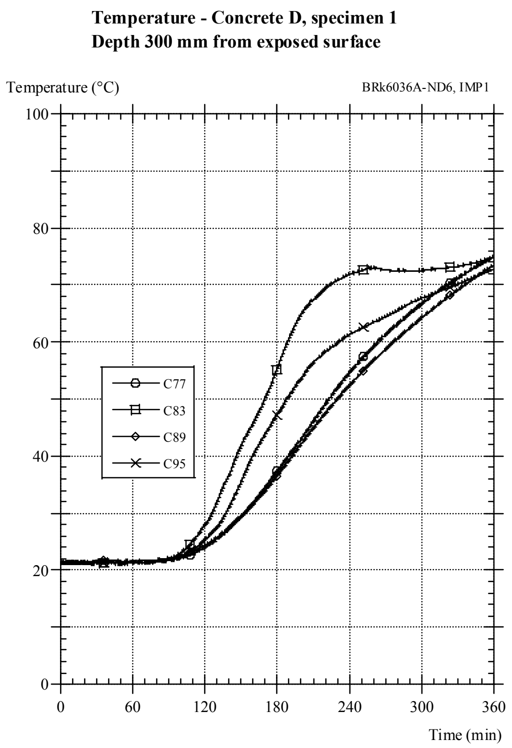

Figure C66. Temperatures 300 mm from the exposed surface.

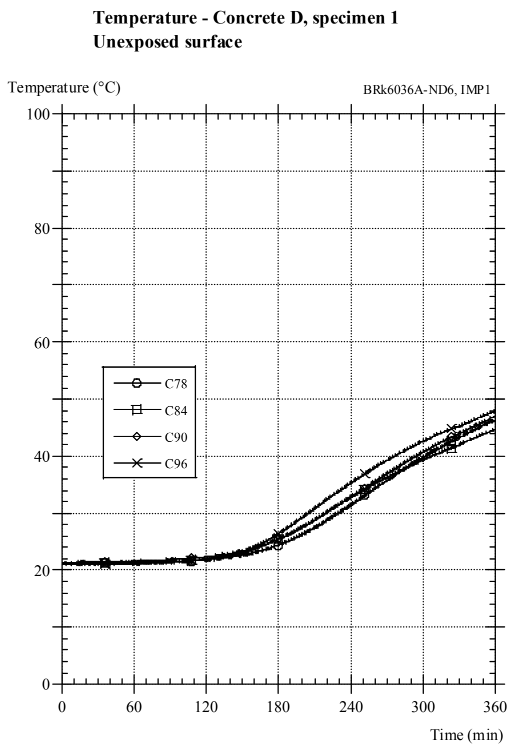

Figure C67. Temperatures on the unexposed surface.

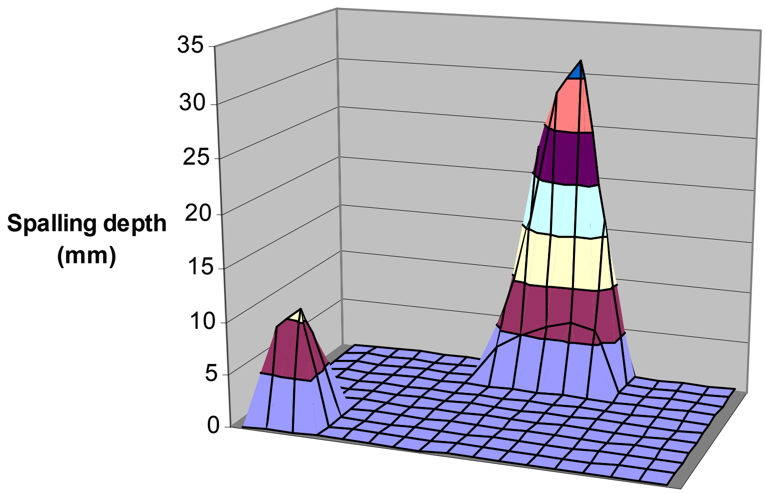

Figure C68. Spalling depth of specimen D1.

Table C7. Spalling depth of specimen D1. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	0	0	0	0	0	0	0	0	0	0	0
200	0	9	7	0	0	0	0	0	0	0	0
300	0	11	8	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0	0	0	0	0
600	0	0	0	0	0	0	0	0	0	0	0
700	0	0	0	0	0	0	0	0	0	0	0
800	0	0	0	0	0	0	0	0	3	7	2
900	0	0	0	0	0	0	0	0	5	16	23
1000	0	0	0	0	0	0	0	0	6	29	21
1100	0	0	0	0	0	0	0	0	7	32	16
1200	0	0	0	0	0	0	0	0	6	16	9
1300	0	0	0	0	0	0	0	0	0	0	0
1400	0	0	0	0	0	0	0	0	0	0	0
1500	0	0	0	0	0	0	0	0	0	0	0
1600	0	0	0	0	0	0	0	0	0	0	0
1700	0	0	0	0	0	0	0	0	0	0	0

C11 – Measurements on specimen D2

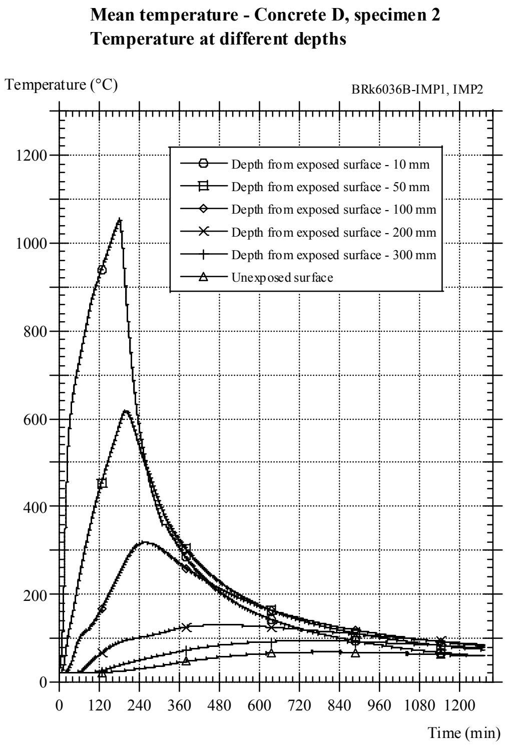

Figure C69. Mean temperatures.

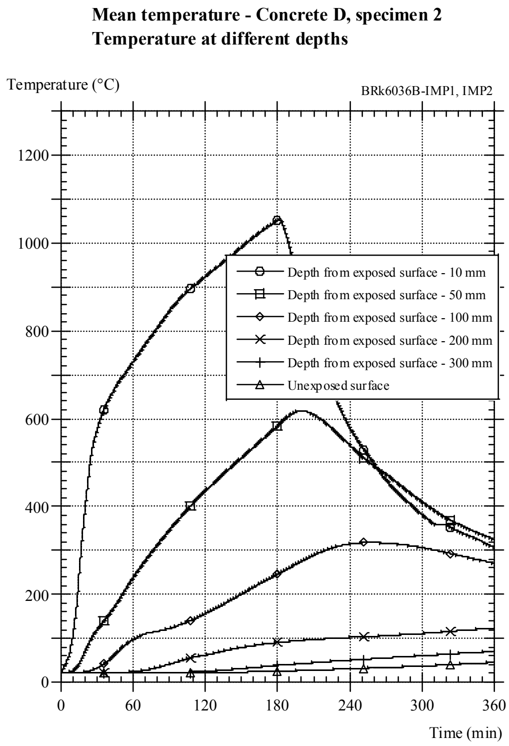

Figure C70. Mean temperatures.

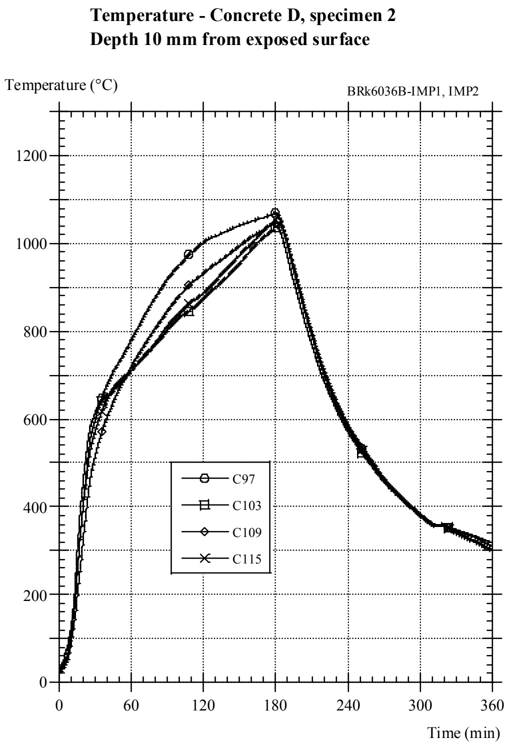

Figure C71. Temperatures 10 mm from the exposed surface.

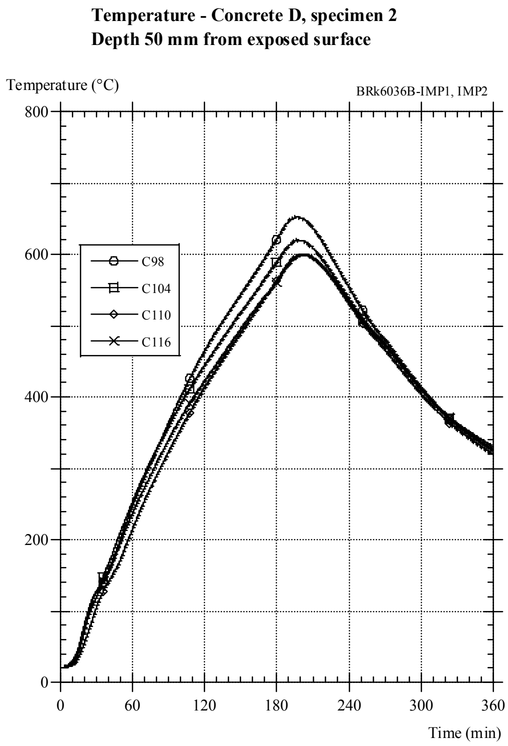

Figure C72. Temperatures 50 mm from the exposed surface.

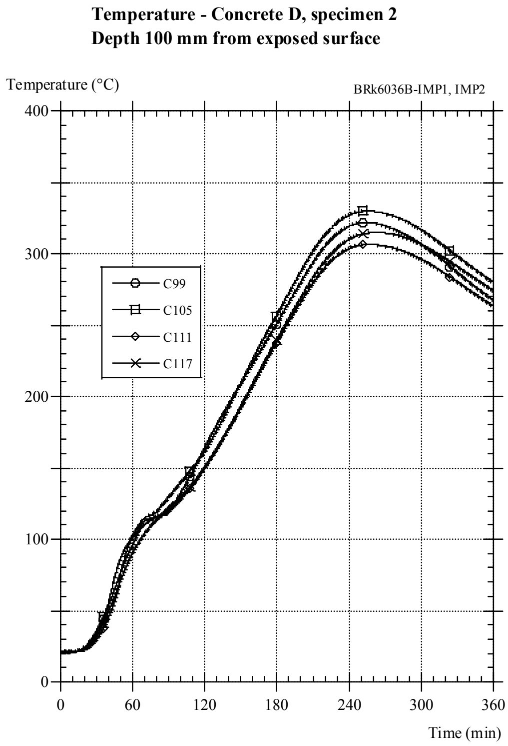

Figure C73. Temperatures 100 mm from the exposed surface.

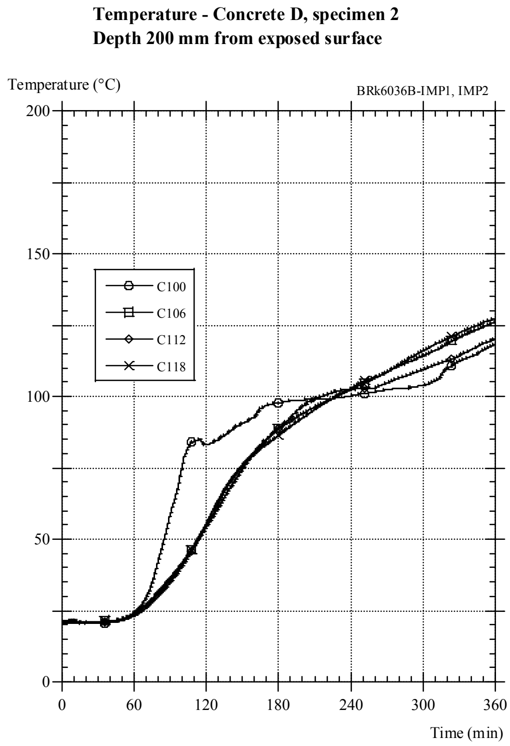

Figure C74. Temperatures 200 mm from the exposed surface.

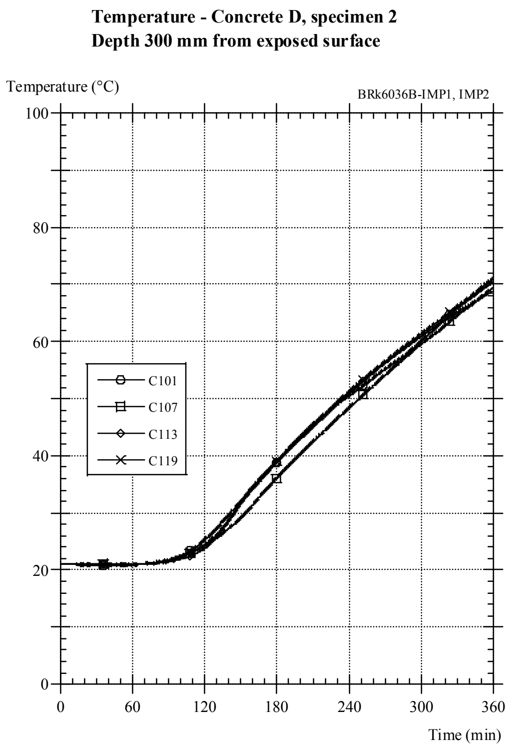

Figure C75. Temperatures 300 mm from the exposed surface.

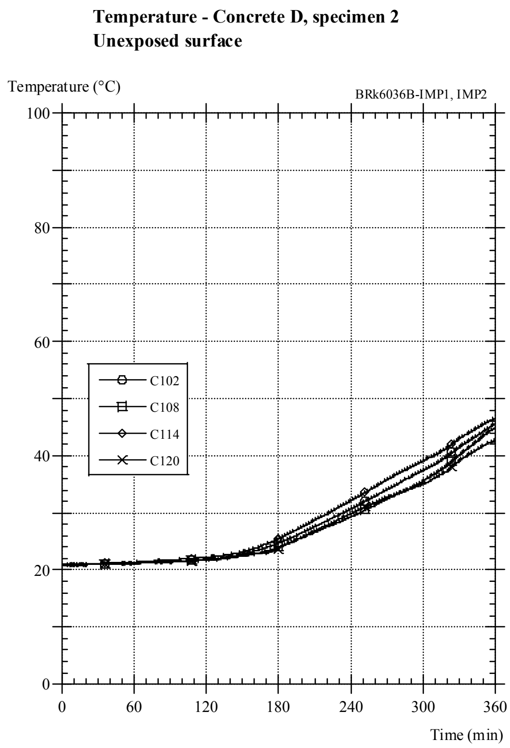

Figure C76. Temperatures on the unexposed surface.

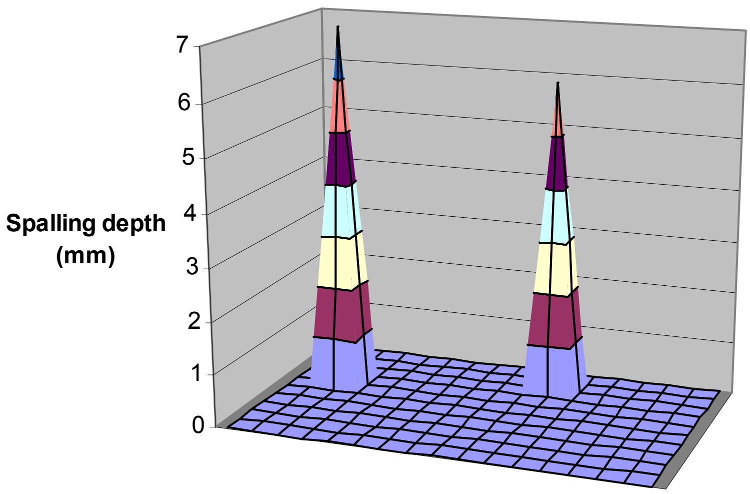

Figure C77. Spalling depth of specimen D2.

Table C8. Spalling depth of specimen D2. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	0	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	7	0	0	0	0
400	0	0	0	0	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0	0	0	0	0
600	0	0	0	0	0	0	0	0	0	0	0
700	0	0	0	0	0	0	0	0	0	0	0
800	0	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0	0	0	0	0
1100	0	0	0	0	0	0	0	0	6	0	0
1200	0	0	0	0	0	0	0	0	0	0	0
1300	0	0	0	0	0	0	0	0	0	0	0
1400	0	0	0	0	0	0	0	0	0	0	0
1500	0	0	0	0	0	0	0	0	0	0	0
1600	0	0	0	0	0	0	0	0	0	0	0
1700	0	0	0	0	0	0	0	0	0	0	0

C12 – Temperatures in columns D10 and D11

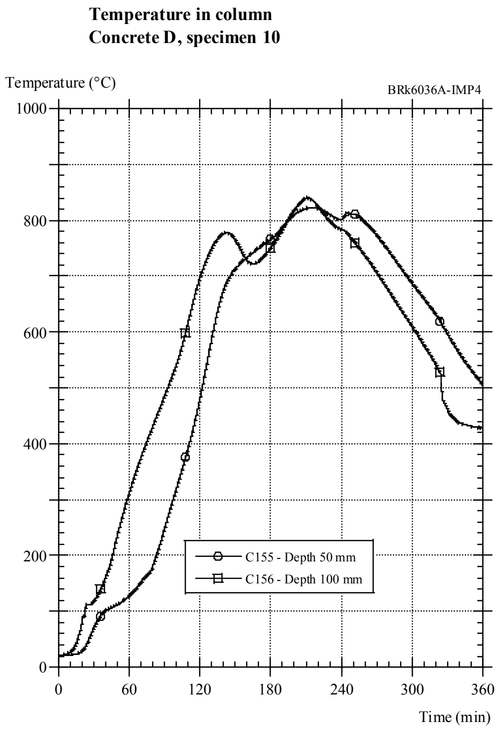

Figure C78. Temperatures at different depths of column D 10.

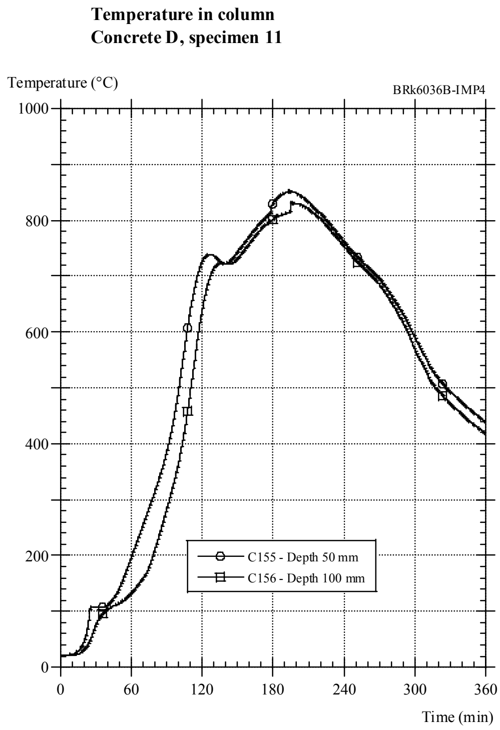

Figure C79. Temperatures at different depths of column D 11.

C13 – Measurements on specimen E1

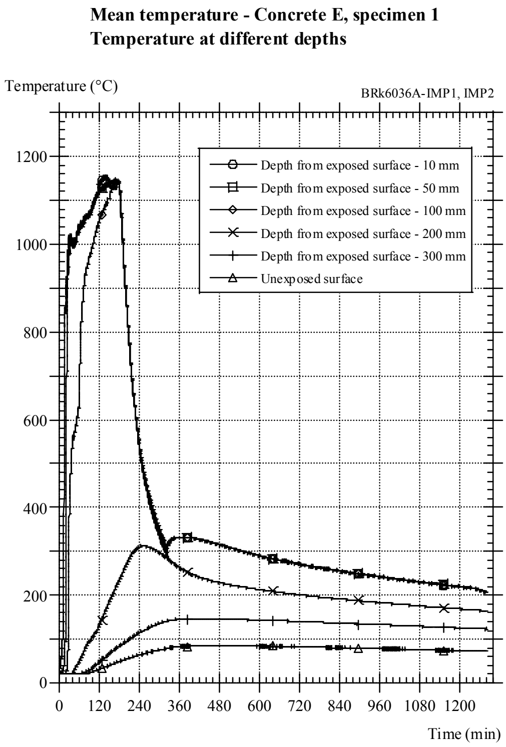

Figure C80. Mean temperatures.

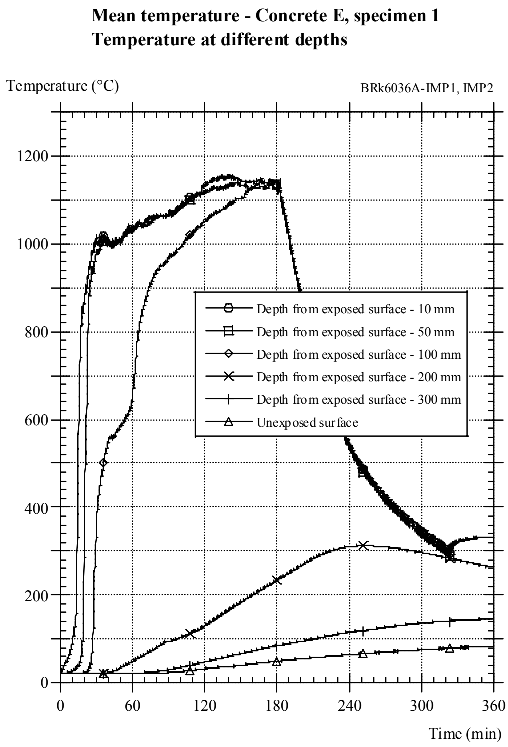

Figure C81. Mean temperatures.

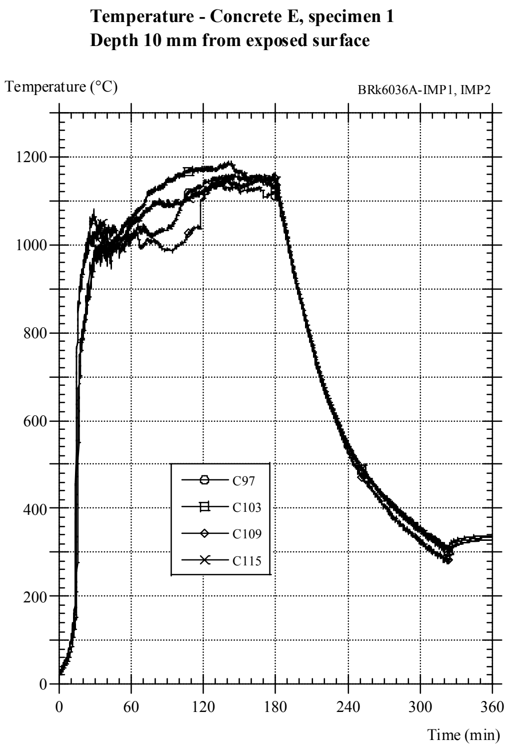

Figure C82. Temperatures 10 mm from the exposed surface.

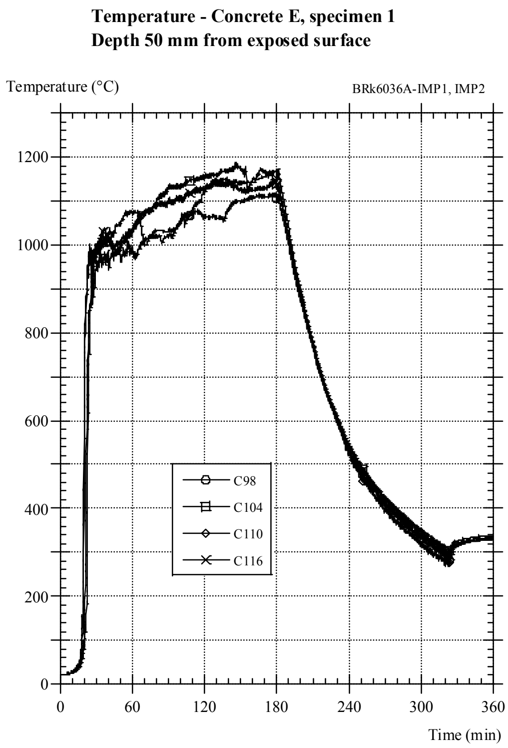

Figure C83. Temperatures 50 mm from the exposed surface.

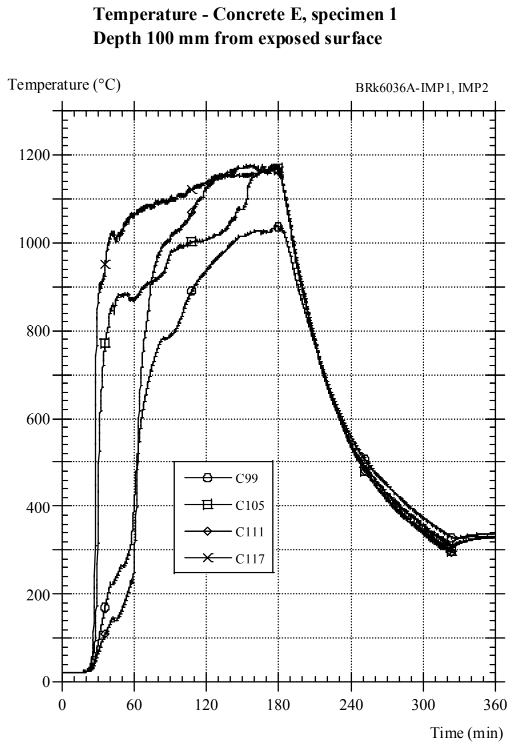

Figure C84. Temperatures 100 mm from the exposed surface.

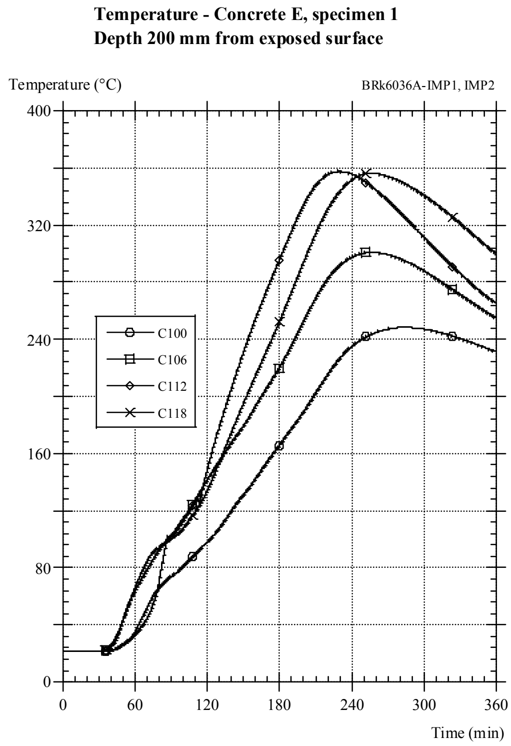

Figure C85. Temperatures 200 mm from the exposed surface.

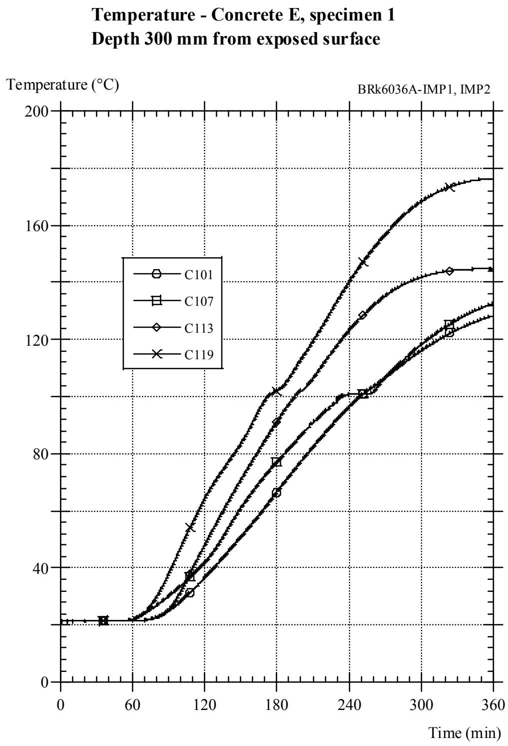

Figure C86. Temperatures 300 mm from the exposed surface.

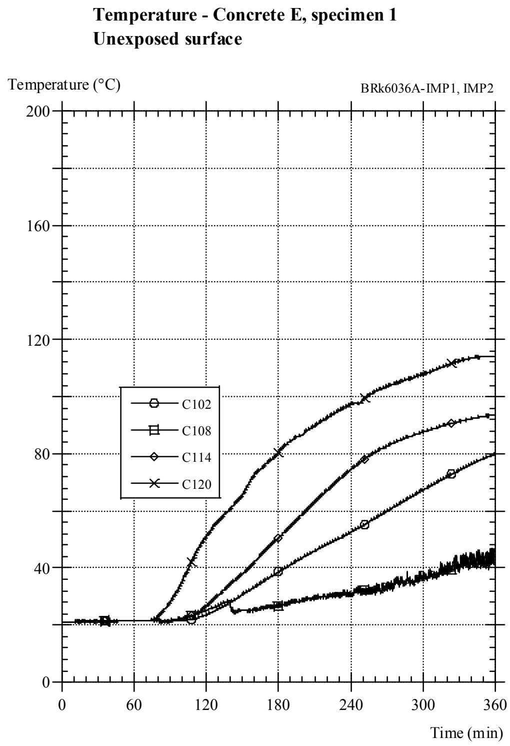

Figure C87. Temperatures on the unexposed surface.

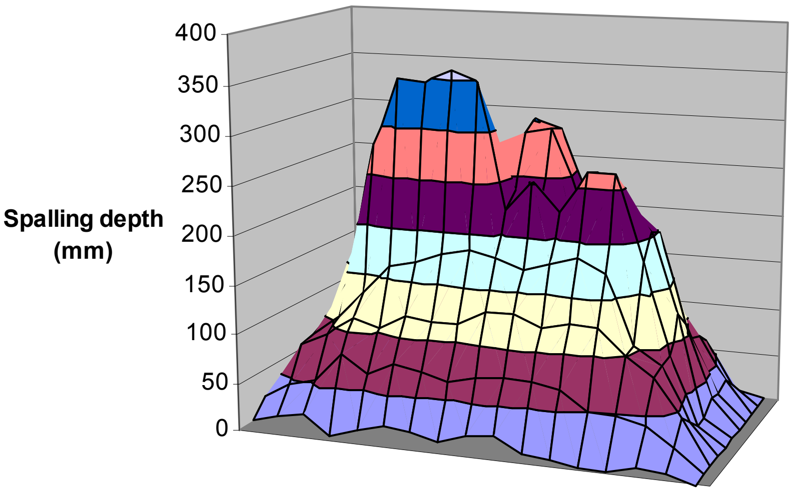

Figure C88. Spalling depth of specimen E1.

Table C9. Spalling depth of specimen E1. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	14	29	17	31	32	24	33	22	16	10	10
200	20	46	79	84	90	96	83	74	74	67	10
300	26	53	94	104	138	184	113	80	113	89	24
400	7	83	112	132	280	237	196	92	118	108	25
500	15	65	104	161	349	281	182	121	138	101	28
600	23	78	120	168	347	289	213	165	173	137	32
700	20	73	116	179	360	326	269	179	175	140	20
800	13	65	116	184	349	281	256	234	152	98	24
900	22	71	132	179	222	237	292	301	151	98	15
1000	25	75	133	170	253	231	297	294	157	95	26
1100	11	74	120	179	224	218	231	227	144	95	38
1200	8	68	127	186	267	261	194	155	129	87	43
1300	3	50	125	172	266	237	182	134	106	60	33
1400	2	49	101	103	181	204	198	134	88	74	41
1500	10	43	81	86	89	123	107	85	80	68	28
1600	7	24	44	33	19	19	31	28	34	21	7
1700	0	1	0	0	1	1	1	0	0	1	1

C14 – Measurements on specimen E2

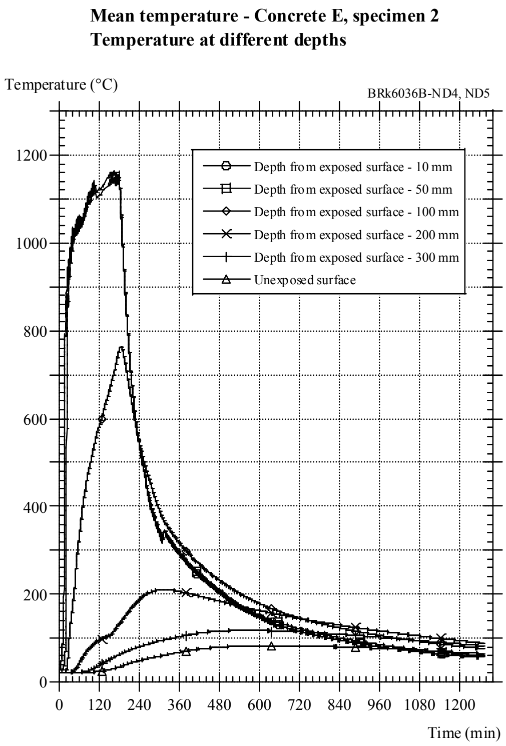

Figure C89. Mean temperatures.

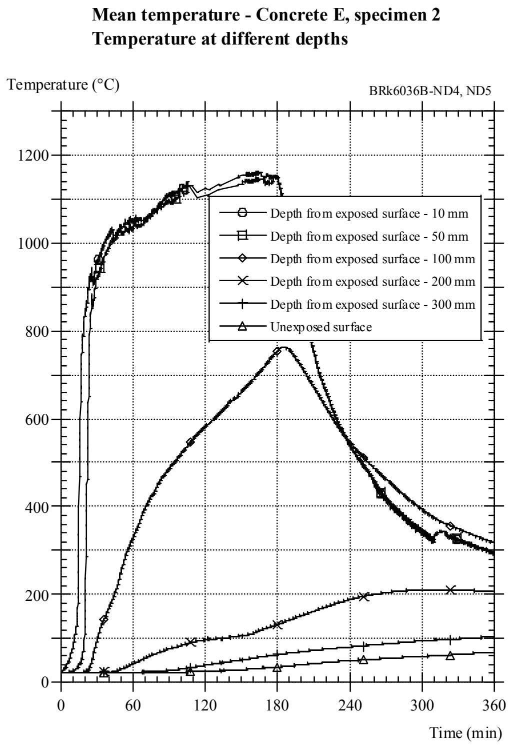

Figure C90. Mean temperatures.

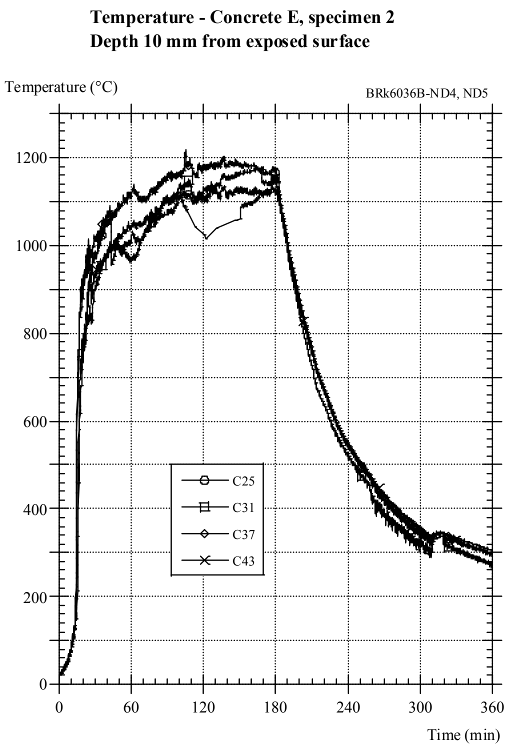

Figure C91. Temperatures 10 mm from the exposed surface.

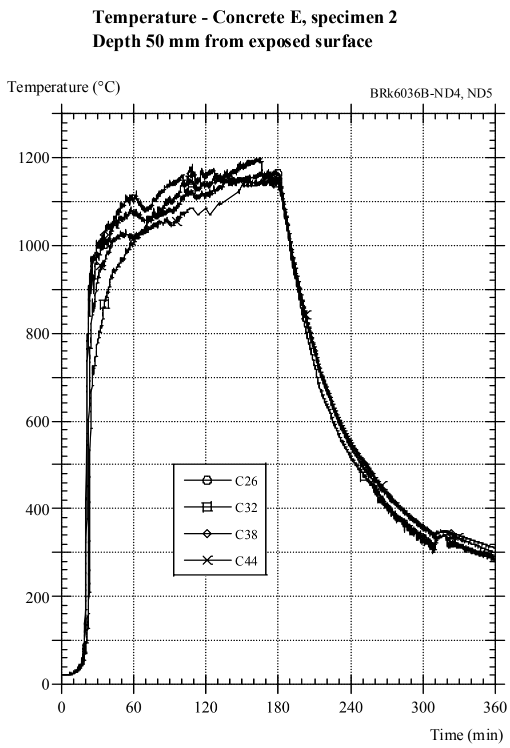

Figure C92. Temperatures 50 mm from the exposed surface.

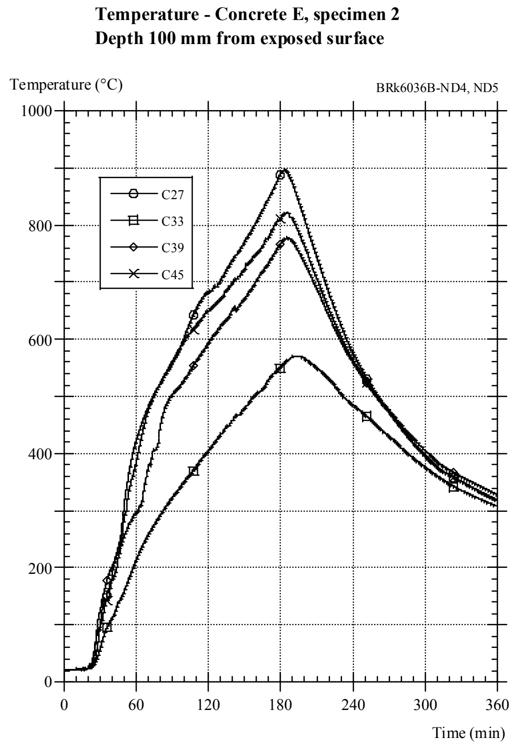

Figure C93. Temperatures 100 mm from the exposed surface.

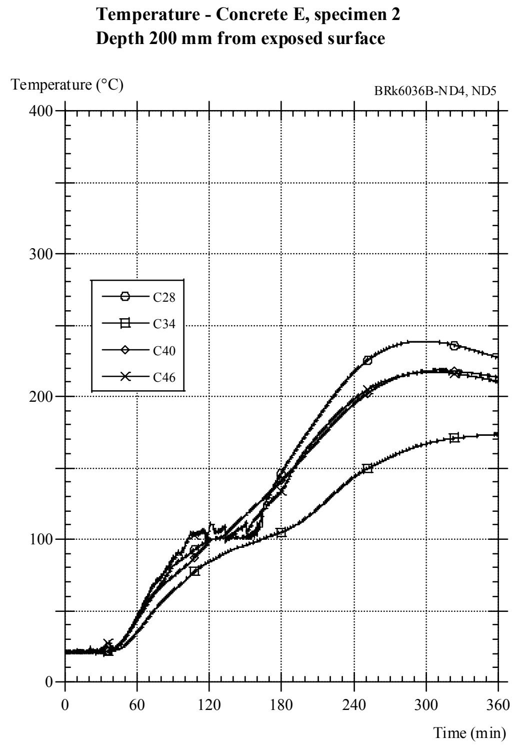

Figure C94. Temperatures 200 mm from the exposed surface.

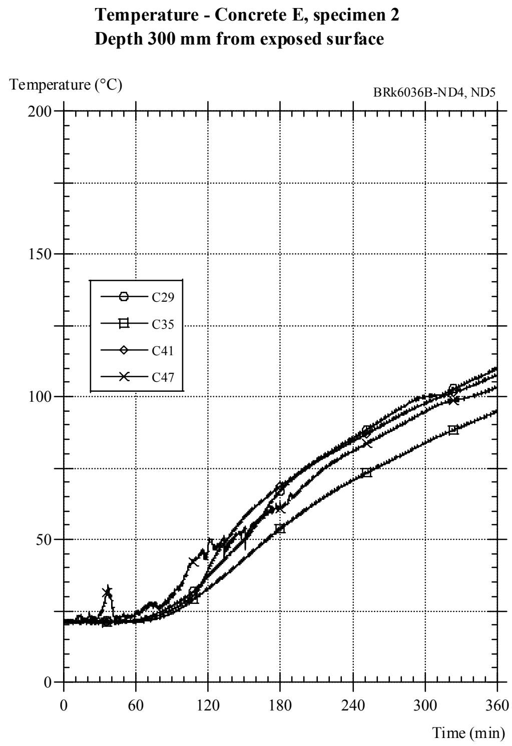

Figure C95. Temperatures 300 mm from the exposed surface.

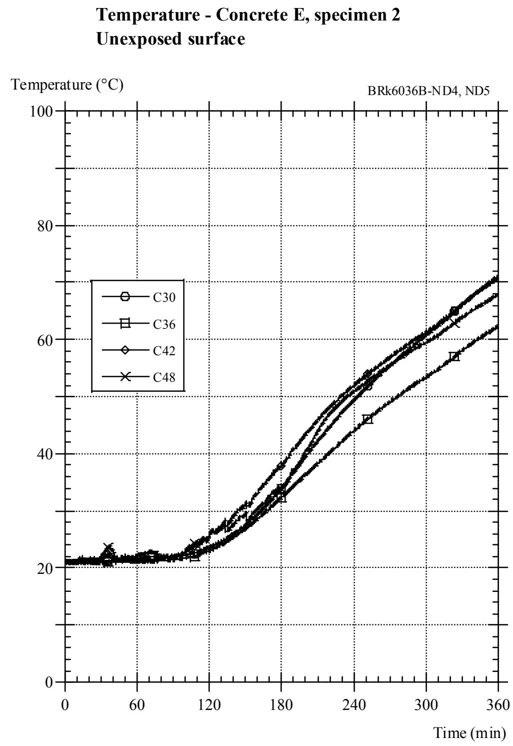

Figure C96. Temperatures on the unexposed surface.

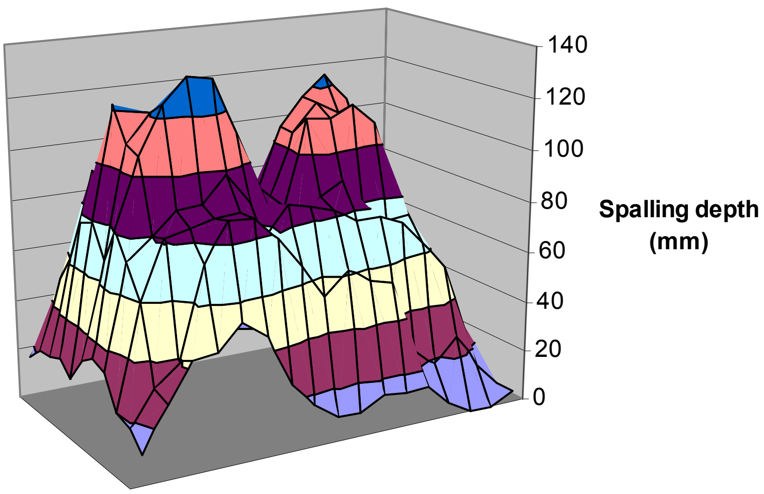

Figure C97. Spalling depth of specimen E2.

Table C10. Spalling depth of specimen E2. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	12	18	20	32	34	30	20	25	22	22	16
200	28	31	60	72	81	67	79	77	60	49	29
300	43	39	82	80	107	109	122	86	93	70	37
400	44	73	84	88	125	120	111	87	80	67	20
500	53	88	86	89	134	123	107	74	83	65	8
600	46	87	87	99	132	105	86	82	76	62	23
700	26	78	76	87	111	72	74	75	75	55	23
800	16	66	87	79	89	76	70	76	63	61	22
900	10	53	85	74	80	82	83	72	75	47	12
1000	9	62	82	85	113	106	106	80	70	36	12
1100	14	56	77	90	112	116	117	75	70	35	10
1200	13	54	77	74	116	111	124	99	88	56	10
1300	14	25	73	72	108	98	114	95	88	61	4
1400	5	18	64	73	80	90	89	82	78	40	12
1500	0	27	53	51	58	54	61	61	55	17	9
1600	0	14	28	32	24	35	22	20	15	8	0
1700	4	4	4	4	4	4	4	4	4	4	4

C15 – Measurements on specimen F1

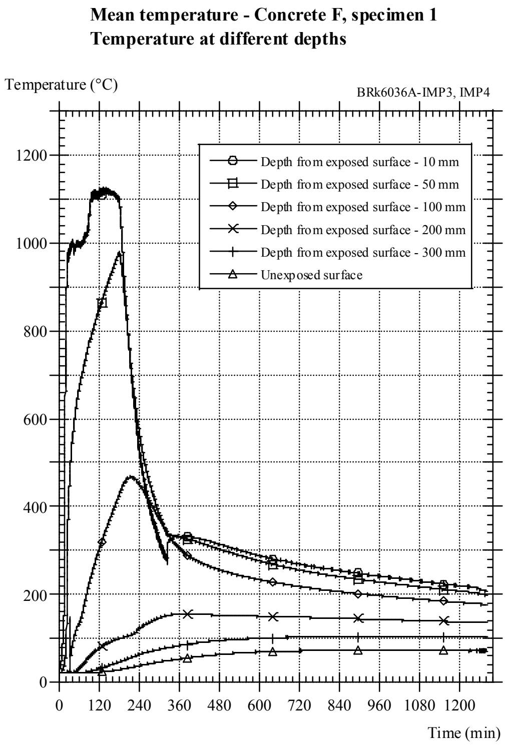

Figure C98. Mean temperatures.

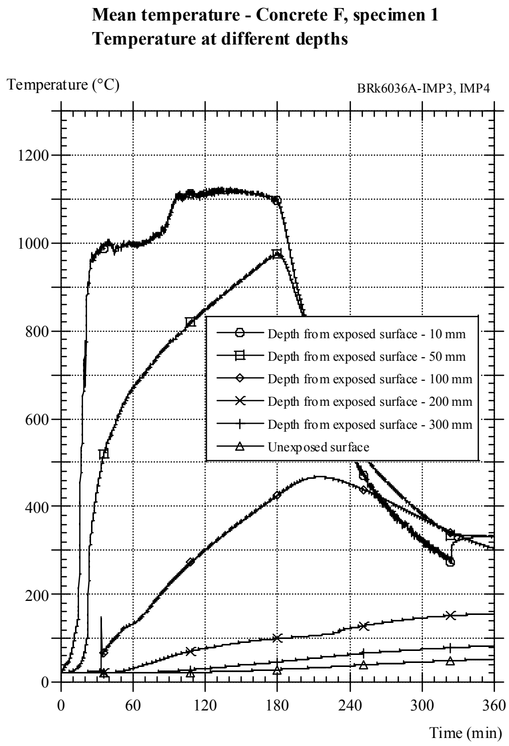

Figure C99. Mean temperatures.

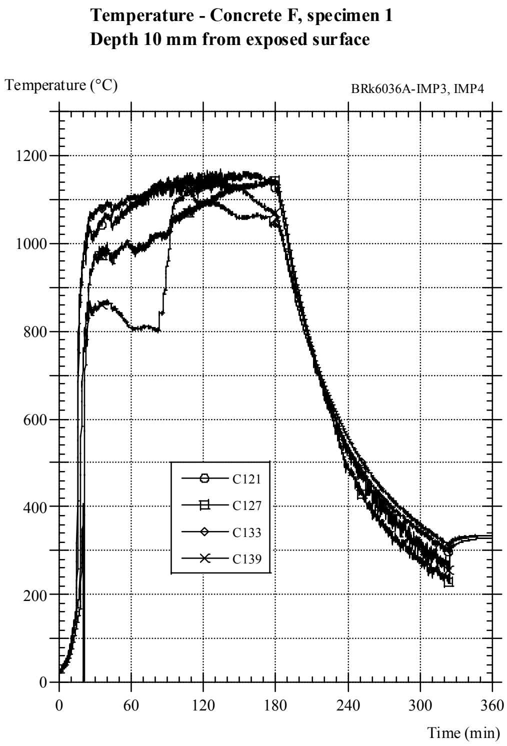

Figure C100. Temperatures 10 mm from the exposed surface.

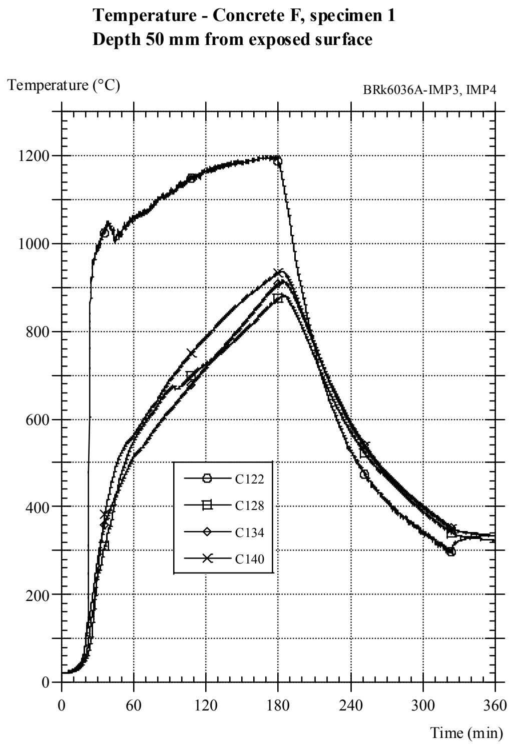

Figure C101. Temperatures 50 mm from the exposed surface.

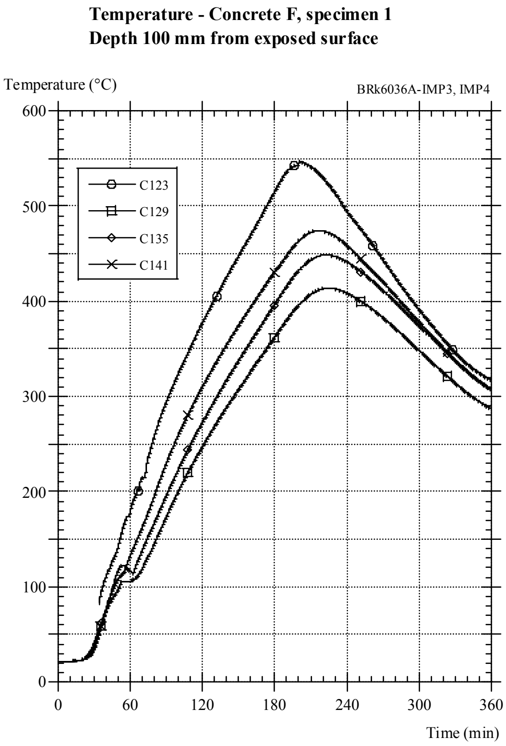

Figure C102. Temperatures 100 mm from the exposed surface.

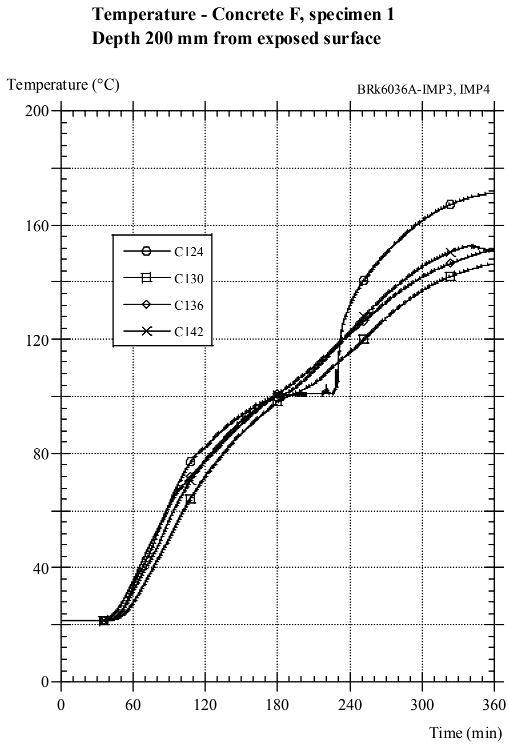

Figure C103. Temperatures 200 mm from the exposed surface.

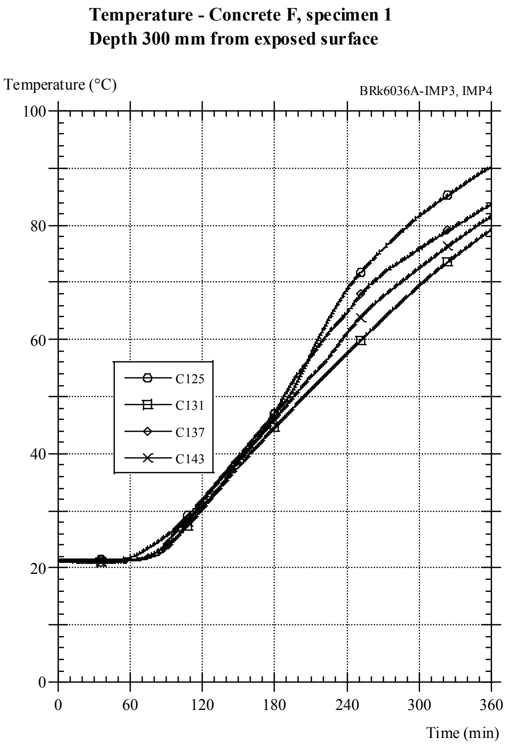

Figure C104. Temperatures 300 mm from the exposed surface.

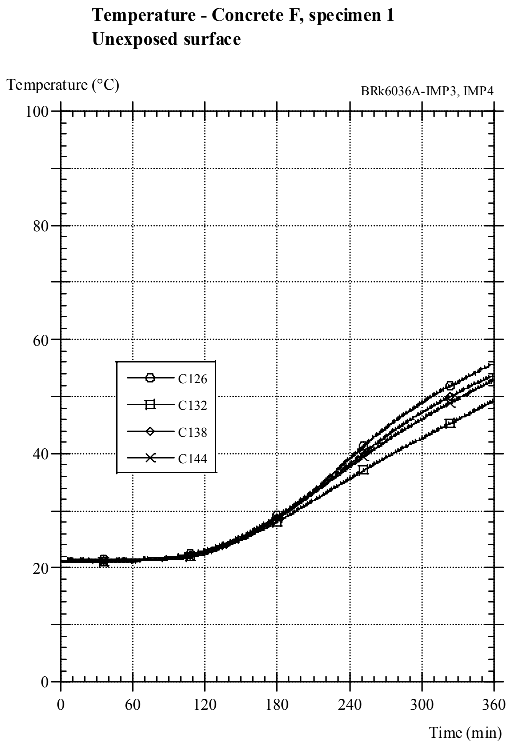

Figure C105. Temperatures on the unexposed surface.

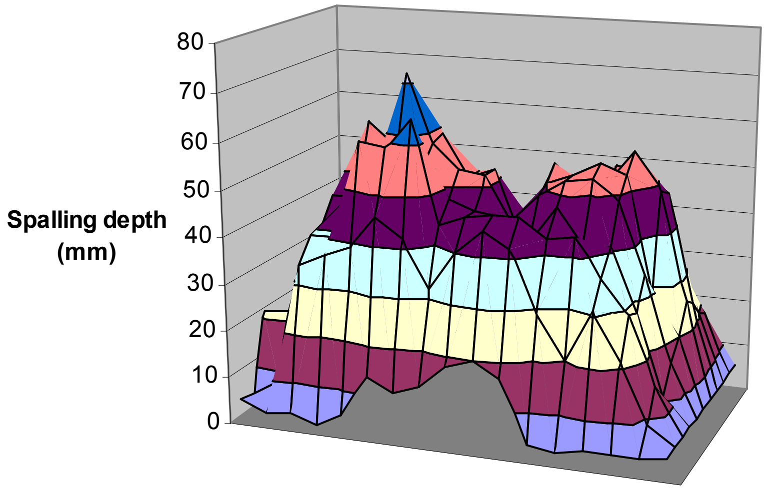

Figure C106. Spalling depth of specimen F1.

Table C11. Spalling depth of specimen F1. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	6	5	22	14	7	10	11	14	8	0	0
200	3	8	22	20	16	23	25	30	24	25	0
300	4	34	39	40	45	32	38	40	43	31	8
400	2	37	39	46	45	60	51	48	38	28	9
500	5	39	60	50	54	56	47	53	37	28	11
600	14	46	59	57	72	56	49	44	36	22	0
700	11	42	65	54	58	59	39	44	28	12	0
800	13	32	44	48	53	50	50	38	30	18	0
900	18	40	46	46	52	52	47	38	25	21	0
1000	20	45	47	45	43	38	41	31	19	20	0
1100	17	42	47	40	49	50	53	45	36	17	0
1200	4	29	43	48	52	52	48	45	34	23	9
1300	3	20	44	41	53	55	50	52	34	29	25
1400	4	31	36	41	49	53	57	51	39	24	22
1500	4	21	29	28	34	28	49	47	33	27	22
1600	4	9	15	11	16	20	26	24	20	18	7
1700	5	5	5	5	5	5	5	5	5	5	5

C16 – Measurements on specimen F2

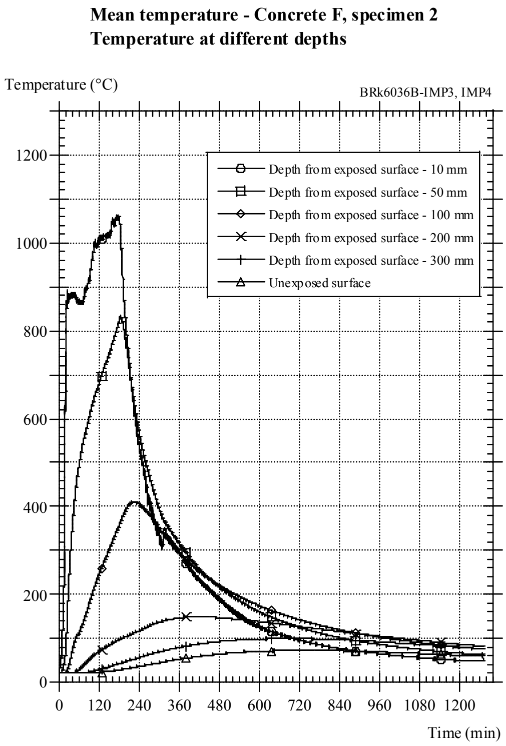

Figure C107. Mean temperatures.

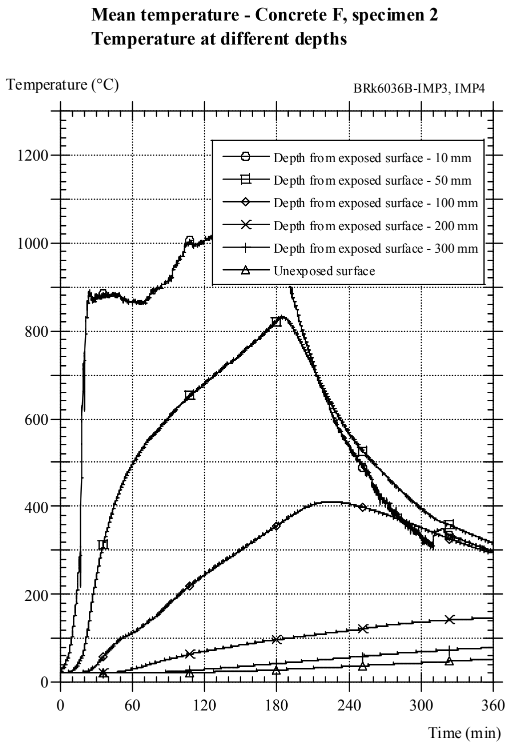

Figure C108. Mean temperatures.

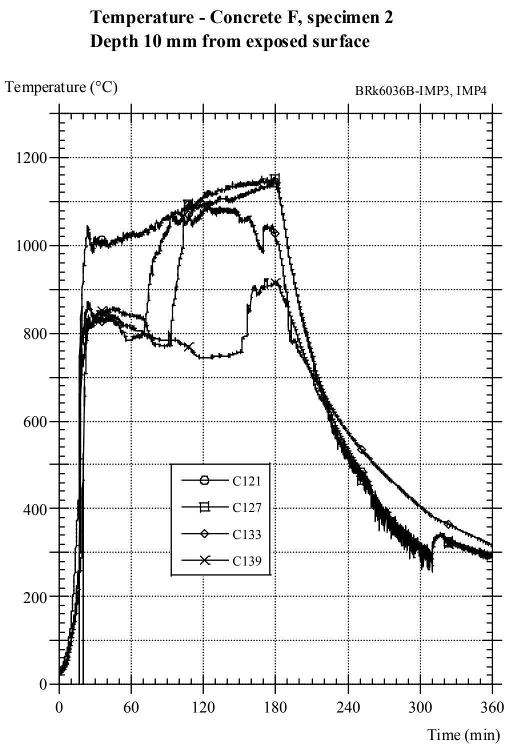

Figure C109. Temperatures 10 mm from the exposed surface.

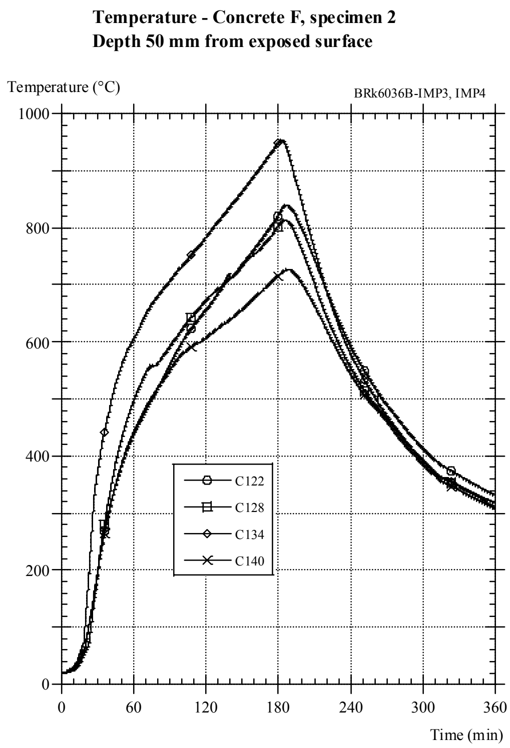

Figure C110. Temperatures 50 mm from the exposed surface.

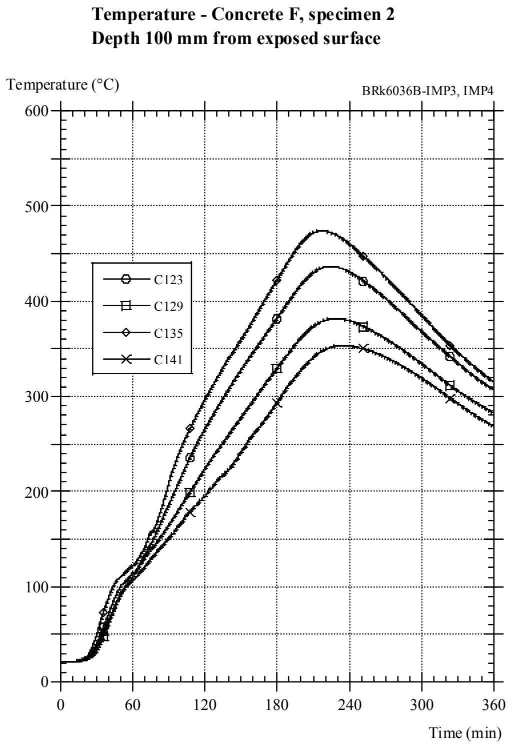

Figure C111. Temperatures 100 mm from the exposed surface.

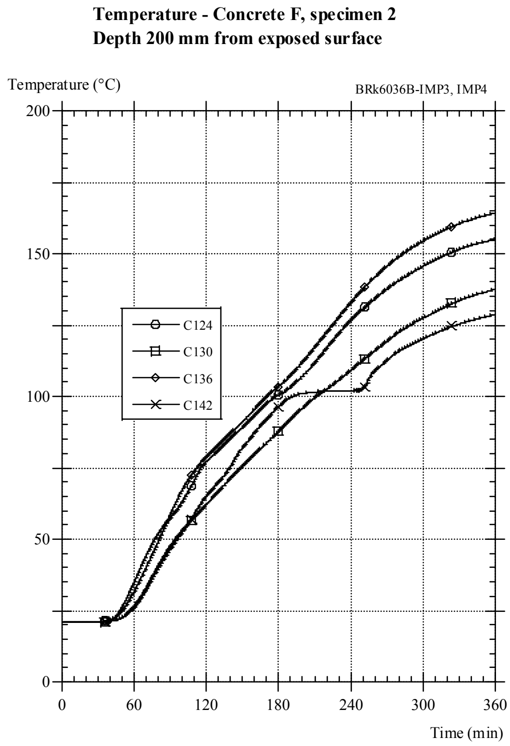

Figure C112. Temperatures 200 mm from the exposed surface.

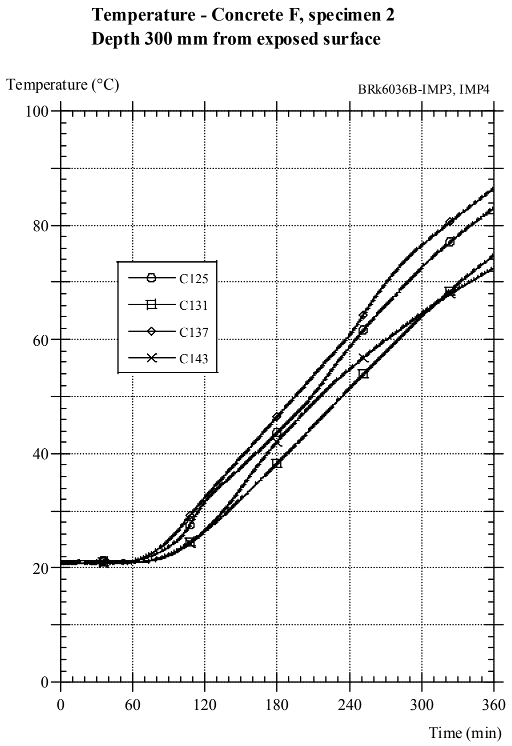

Figure C113. Temperatures 300 mm from the exposed surface.

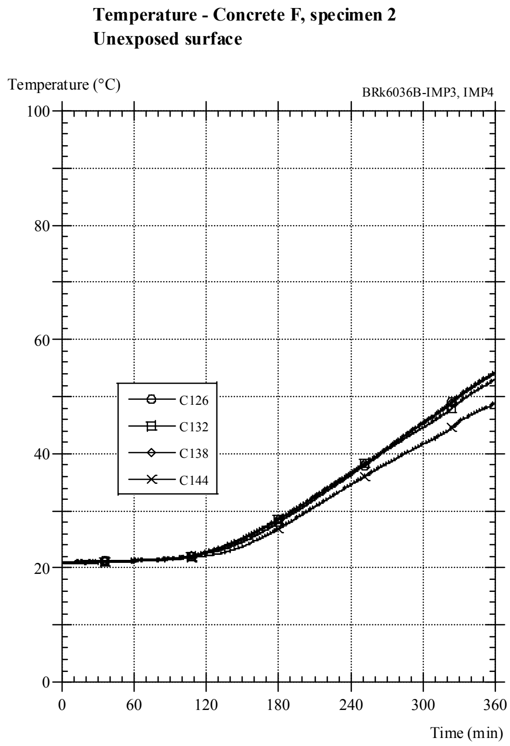

Figure C114. Temperatures on the unexposed surface.

C17 - Measurements on small slabs of tunnel concrete

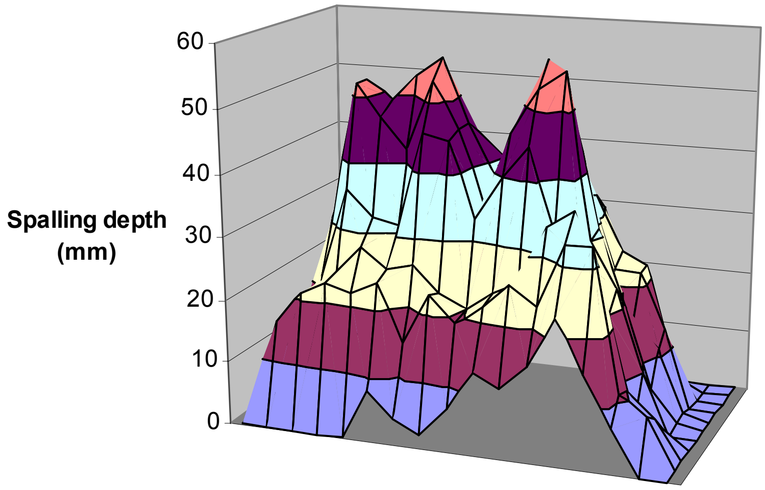

Figure C115. Spalling depth of specimen F2.

Table C12. Spalling depth of specimen F2. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	100	200	300	400	500	600	700	800	900	1000	1100
100	0	1	1	1	2	1	2	8	10	3	1
200	0	16	16	13	8	13	23	26	15	21	6
300	0	21	16	22	31	38	32	27	32	28	24
400	0	23	24	36	52	52	41	31	34	37	17
500	0	22	28	32	47	49	36	31	27	32	13
600	8	24	25	31	42	53	31	35	30	26	20
700	4	15	26	46	53	56	45	38	27	30	10
800	2	23	22	45	46	46	44	31	30	18	8
900	7	19	20	33	34	38	40	28	29	21	11
1000	13	22	23	40	46	44	41	28	32	27	22
1100	11	26	25	45	53	57	49	45	34	32	10
1200	15	23	34	32	56	48	42	34	33	30	14
1300	23	33	37	28	30	31	17	22	24	16	5
1400	15	33	26	20	23	19	15	22	22	12	0
1500	7	11	10	4	10	6	11	13	7	2	0
1600	0	8	6	3	0	1	1	0	0	0	0
1700	0	0	0	0	0	0	0	0	0	0	0

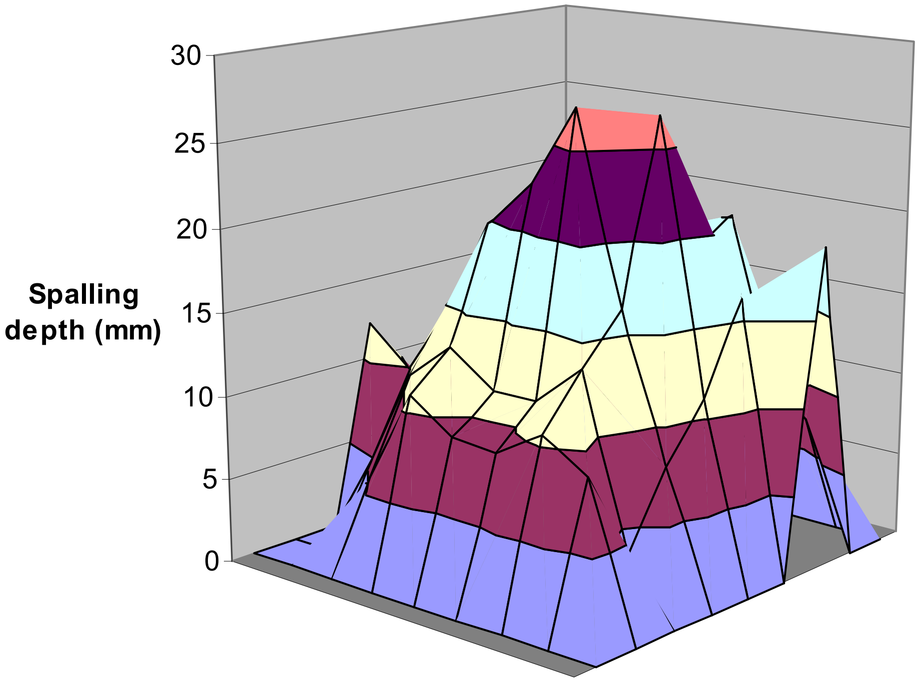

Figure C116. Spalling depth of small slab specimen A23.

Table C13. Spalling depth of specimen A23. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	0	50	100	150	200	250	300	350	400
0	0	0	0	12	6	3	4	6	9
50	0	0	5	10	7	12	12	9	0
100	0	5	11	14	18	18	14	16	0
150	0	11	13	20	22	22	17	8	0
200	0	9	11	23	24	19	17	8	0
250	0	9	11	27	7	19	17	9	0
300	0	11	14	16	27	19	20	11	0
350	0	9	4	8	11	16	11	8	0
400	0	0	0	0	0	0	19	0	0

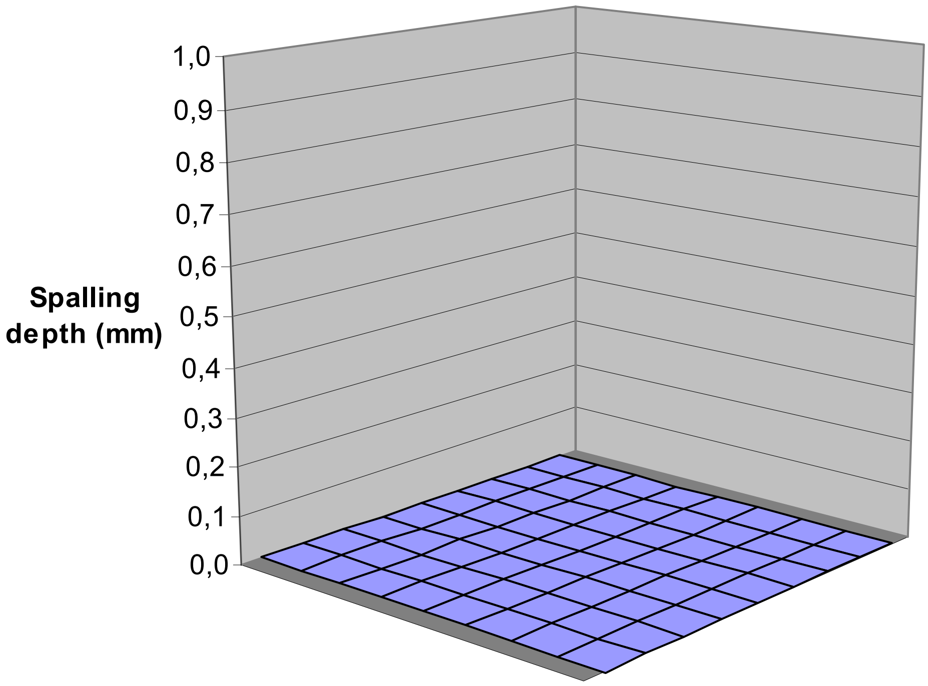

Figure C117. Spalling depth of small slab specimen B23.

Table C14. Spalling depth of specimen B23. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	0	50	100	150	200	250	300	350	400
0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0
250	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0
350	0	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0	0

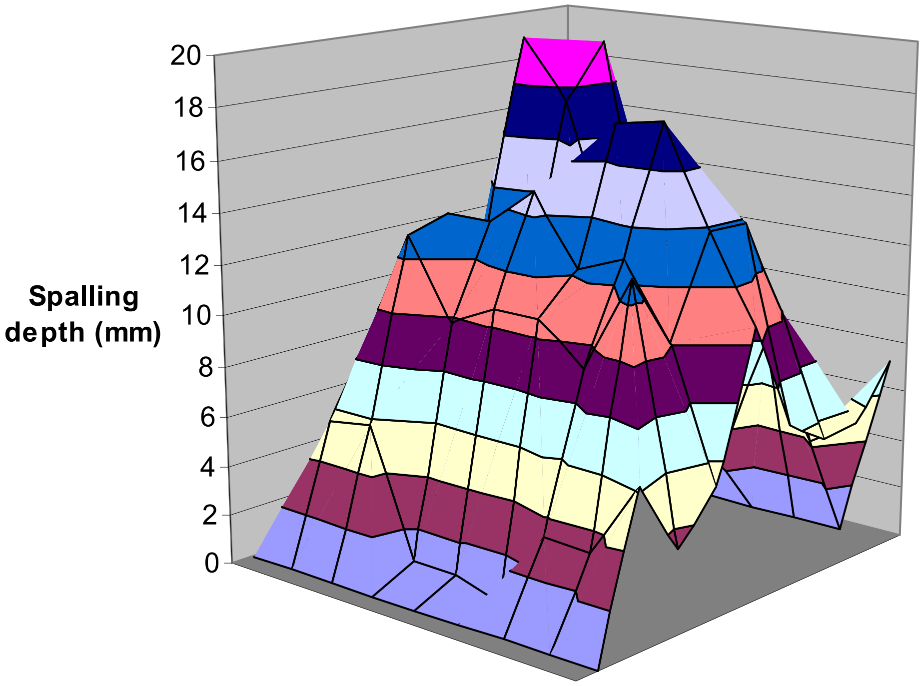

Figure C118. Spalling depth of small slab specimen C23.

Table C15. Spalling depth of specimen C23. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	0	50	100	150	200	250	300	350	400
0	0	0	0	0	0	0	0	0	0
50	0	6	9	6	6	6	5	4	0
100	0	6	13	13	13	20	15	3	0
150	0	1	10	13	10	18	20	7	0
200	0	1	11	15	15	12	12	9	0
250	0	0	11	12	17	15	12	2	0
300	0	3	9	13	18	15	14	8	0
350	0	3	13	10	14	14	10	4	0
400	0	6	3	5	11	6	5	6	8

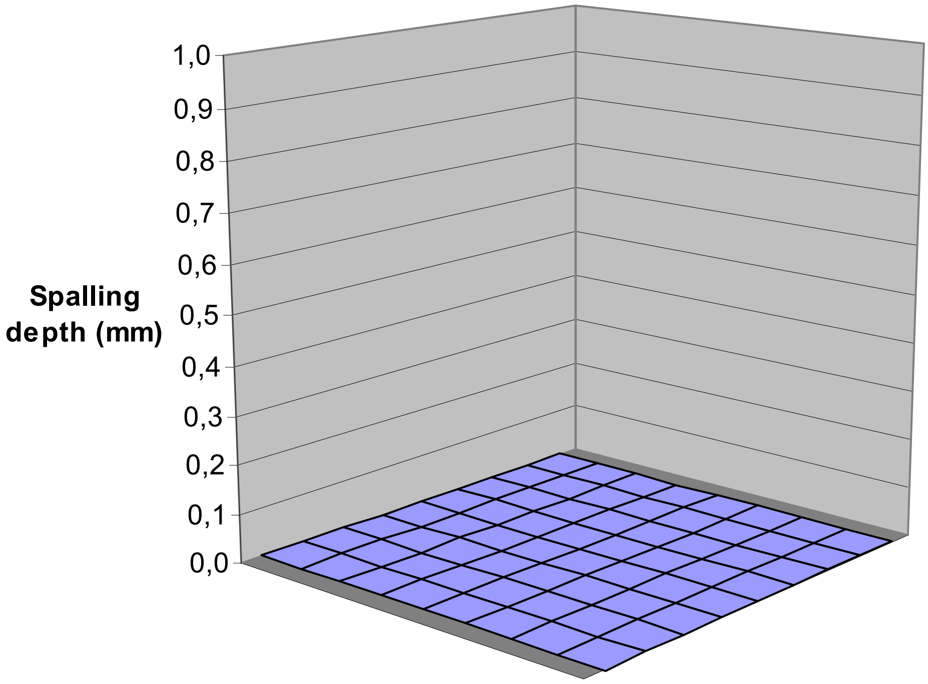

Figure C119. Spalling depth of small slab specimen D22.

Table C16. Spalling depth of specimen D22. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	0	50	100	150	200	250	300	350	400
0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0
250	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0
350	0	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0	0

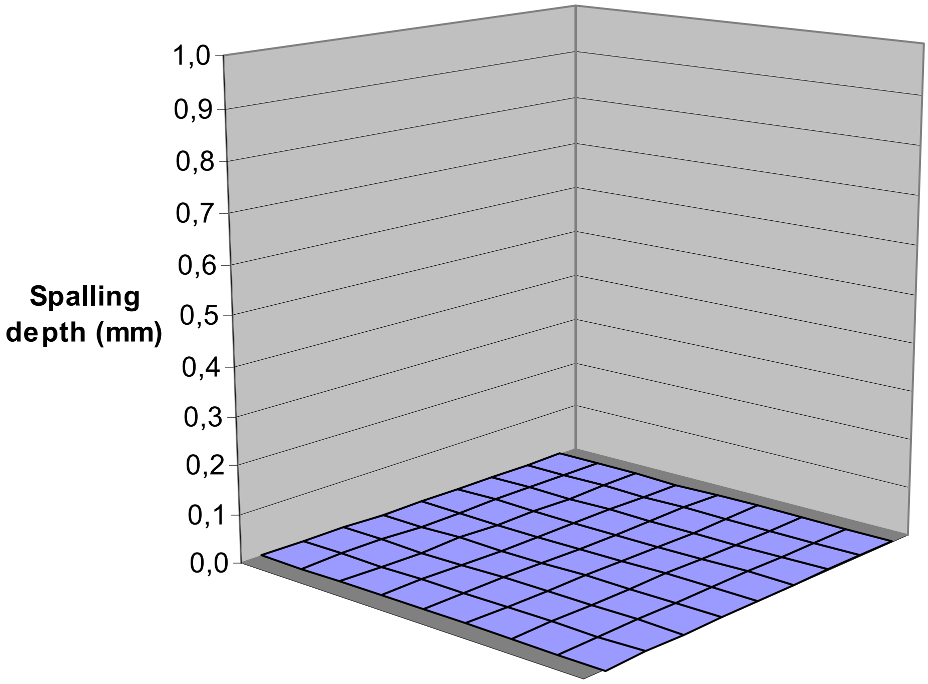

Figure C120. Spalling depth of small slab specimen D23.

Table C17. Spalling depth of specimen D23. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	0	50	100	150	200	250	300	350	400
0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0
250	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0
350	0	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0	0

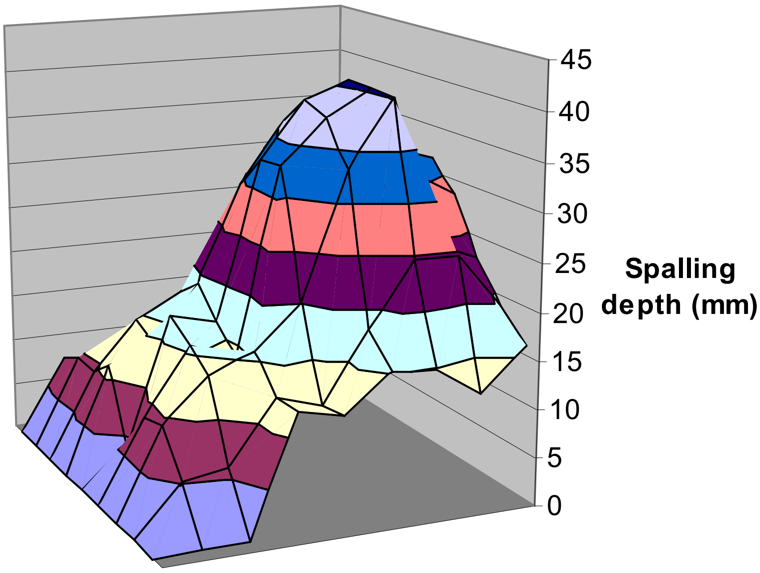

Figure C121. Spalling depth of small slab specimen E22.

Table C18. Spalling depth of specimen E22. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	0	50	100	150	200	250	300	350	400
0	0	0	0	0	0	0	0	0	0
50	8	9	9	11	4	9	9	5	0
100	0	9	14	13	18	16	14	6	0
150	0	13	17	19	16	14	16	12	12
200	0	8	21	29	33	33	20	11	11
250	0	12	32	36	39	38	33	18	15
300	0	22	31	37	41	40	40	25	15
350	12	15	29	32	33	31	25	25	12
400	18	18	24	20	32	29	23	19	16

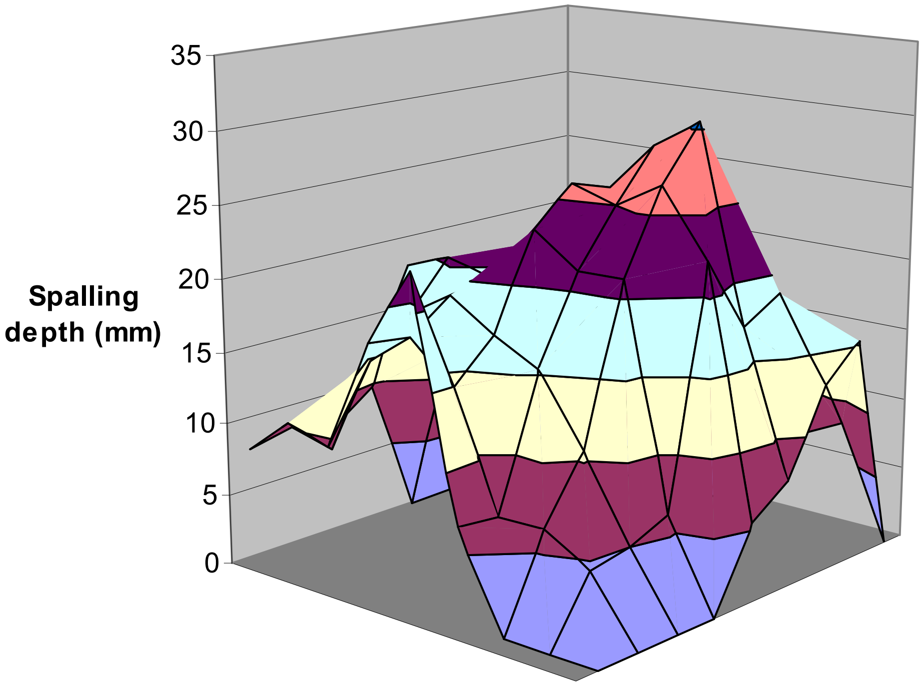

Figure C122. Spalling depth of small slab specimen E23.

Table C19. Spalling depth of specimen E23. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	0	50	100	150	200	250	300	350	400
0	8	8	8	10	0	0	7	5	0
50	10	8	13	19	12	4	8	6	0
100	10	15	17	20	19	16	11	4	0
150	17	17	19	20	21	21	17	4	0
200	23	14	17	23	26	25	18	8	0
250	7	6	15	21	25	28	23	7	0
300	0	6	11	21	27	31	19	15	6
350	0	5	5	6	22	17	19	14	8
400	0	0	0	0	5	7	13	15	0

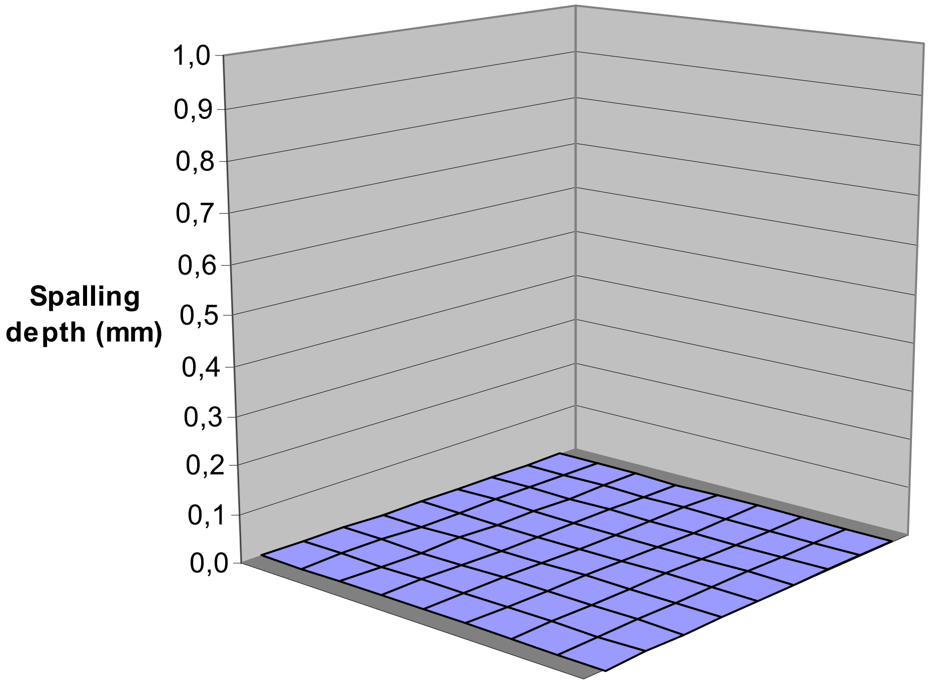

Figure C123. Spalling depth of small slab specimen F22.

Table C20. Spalling depth of specimen F22. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	0	50	100	150	200	250	300	350	400
0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0
250	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0
350	0	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0	0

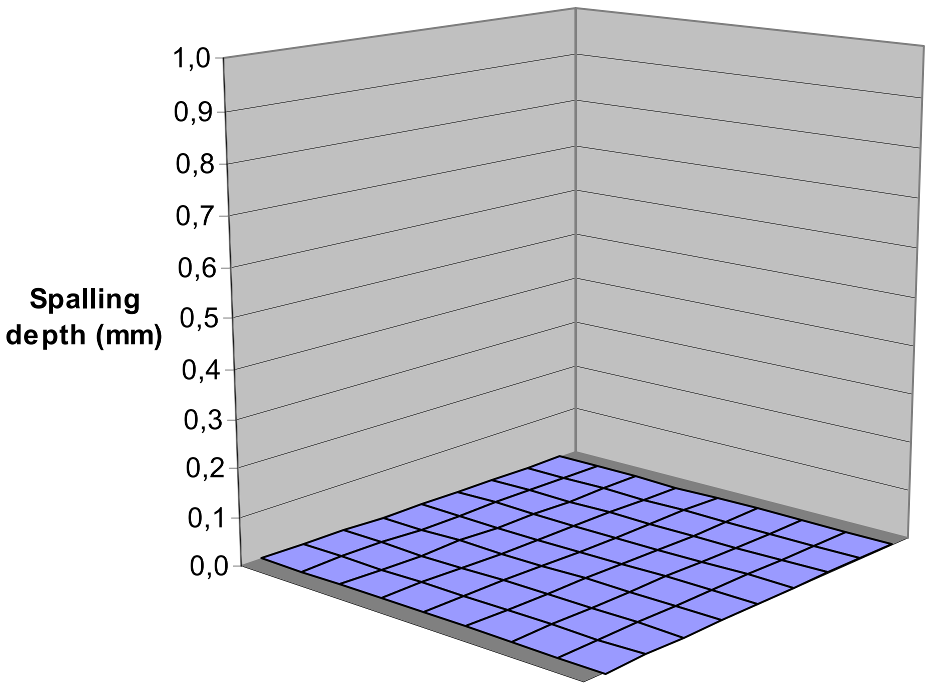

Figure C124. Spalling depth of small slab specimen F23.

Table C21. Spalling depth of specimen F23. Row 1 and column 1 gives position on the specimen. All measures are in mm.

	0	50	100	150	200	250	300	350	400
0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0
250	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0
350	0	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0	0

Appendix D - Photos of large scale test specimens of self-compacting concrete

D1- Manufacturing of specimens

Figure D1. Casting mould with pre-stressed wires for large slabs.

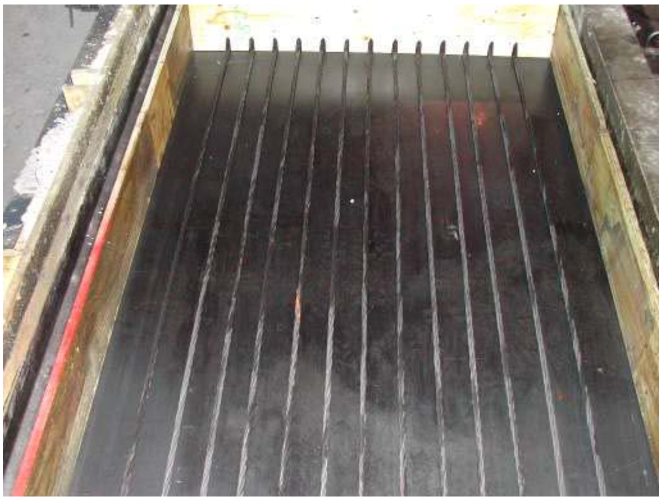

Figure D2. Casting mould with pre-stressed wires for large slabs.

Figure D3. Reinforcement of large slabs.

Figure D4. Casting of large slabs.

Figure D5. Casting of large slabs and protection with plastic foil.

Figure D6. Reinforcement of large beams.

Figure D7. Close-up on mounted thermocouples.

D2 - Large specimens after fire test

Figure D8. Water pouring out at the pre-stressed wires of a large slab.

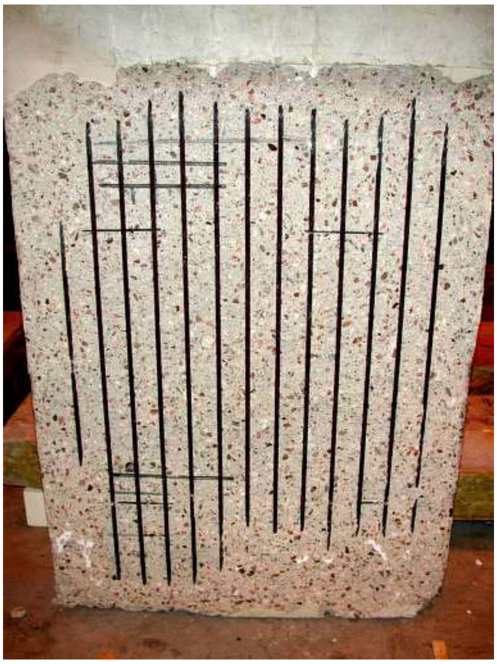

Figure D9. Slab LS 30 01 after the fire test.

Figure D10. Slab LS 40 01 after the fire test.


Figure D11. Slab LS 40 11 after the fire test.


Figure D12. Slab LS 40 11 after the fire test.

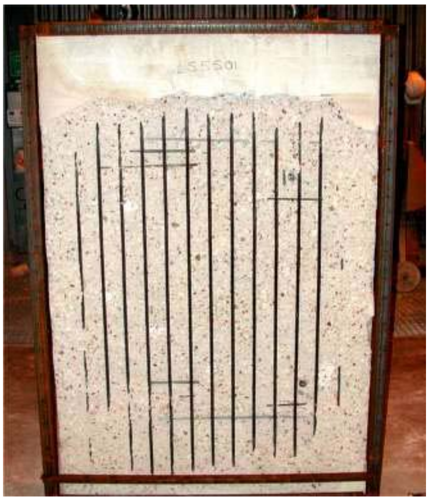
Figure D13. Slab LS 55 01 after the fire test.

Figure D14. Beam LB 40 01 after the fire test.

Figure D15. Beam LB 40 01 after the fire test.

Figure D16. Close-up on beam LB 40 01 after the fire test.

Figure D17. Beam LB 40 11 after the fire test.

Figure D18. Close-up on beam LB 40 11 after the fire test.

Appendix E - Photos of small scale test specimens of self-compacting concrete

E1 - Manufacturing of small scale specimens and specimens before fire test

Figure E1. Casting mould for cylindrical specimens.

Figure E2. Unloaded cylindrical specimen placed in the furnace.

Figure E3. Loaded (left) and unloaded (right) cylindrical specimens placed in the furnace.

Figure E4. Cylindrical specimens placed in the furnace.

Figure E5. Casting mould and reinforcement of small slabs.

Figure E6. Casting moulds and reinforcement for small slabs.

E2 - Small specimens after fire tests

Figure E7. Cylindrical specimens SC 30 01, SC 30 02 (up) and SC 30 03, SC 30 04 (down).

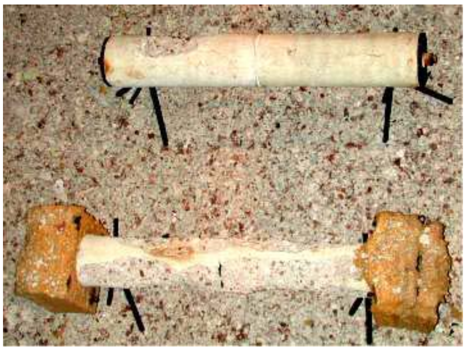

Figure E8. Cylindrical specimens SC 40 01, SC 40 02 (up) and SC 40 03, SC 40 04 (down).

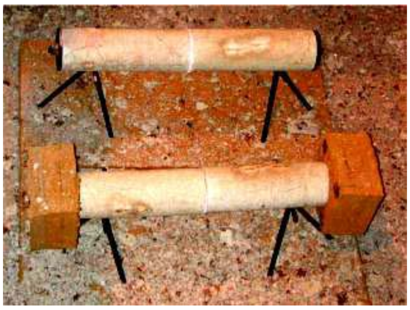

Figure E9. Cylindrical specimens SC 40 11, SC 40 12 (up) and SC 40 13, SC 40 14 (down).

Figure E10. Cylindrical specimens SC 55 01, SC 55 02 (up) and SC 55 03, SC 55 04 (down).

Figure E11. Small slab SS 30 01 during the fire test. Water is pouring out at the edges.


Figure E12. Small slab SS 30 01 after the fire test.


Figure E13. Small slab SS 30 02 during the fire test. Water is pouring out at the edges.

Figure E14. Small slab SS 30 02 after the fire test.

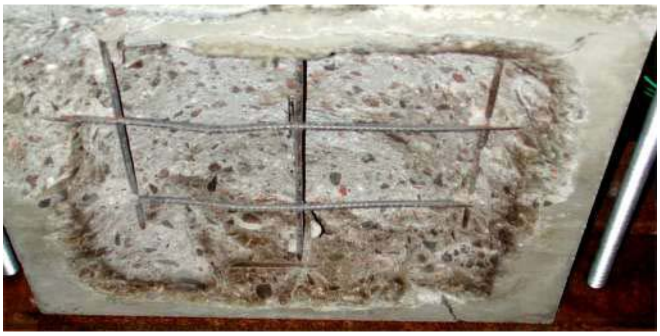

Figure E15. Small slab SS 30 03 after the fire test.

Figure E16. Small slab SS 30 04 during the fire test. Water is pouring out on the top and at the edges.

Figure E17. Small slab SS 30 04 after the fire test.

Figure E18. Some of the material that spalled of from SS 30 04.

Figure E19. Small slab SS 40 01 after the fire test.

Figure E20. Small slab SS 40 02 during the fire test. Water is pouring out at the edges.

Figure E21. Small slab SS 40 02 after the fire test.

Figure E22. Small slab SS 40 03 during the fire test. Water is pouring out on the top and at the edges.

Figure E23. Small slab SS 40 03 after the fire test.

Figure E23. Close-up on small slab SS 40 03 after the fire test.

Figure E24. Small slab SS 40 04 during the fire test. Water is pouring out on the top and at the edges.

Figure E25. Small slab SS 40 04 after the fire test.

Figure E26. Small slab SS 40 04 after the fire test.

Figure E27. Small slab SS 40 11 during the fire test. Water is pouring out at the edges.

Figure E28. Small slab SS 40 11 after the fire test.

Figure E29. Small slab SS 40 12 after the fire test.

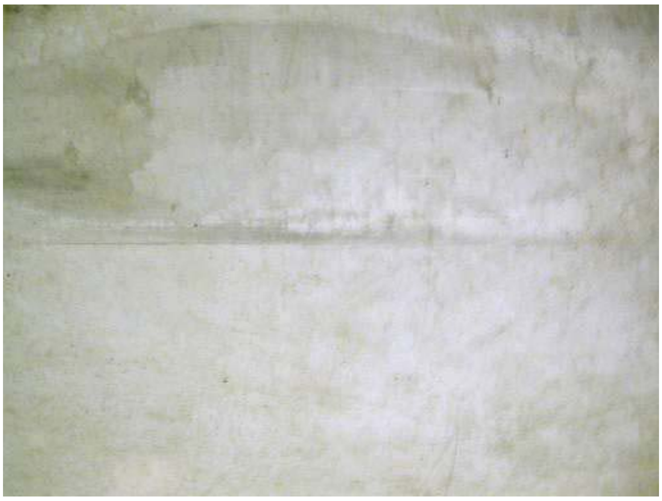
Figure E30. Small slab SS 40 13 after the fire test.


Figure E31. Small slab SS 40 14 after the fire test.


Figure E32. Small slab SS 55 01 after the fire test.

Figure E33. Small slab SS 55 02 after the fire test.

Figure E34. Small slab SS 55 03 during the fire test. A large crack appeared at the edge.

Figure E34. Small slab SS 55 03 after the fire test.

Figure E35. Close-up on small slab SS 55 03 after the fire test.

Figure E36. Small slab SS 55 04 after the fire test.

Appendix F - Photos of test specimens of tunnel concrete

F1 - Specimen manufacturing and placement of specimens in and on the furnace

Figure F1. Reinforcement of large slabs.

Figure F2. Mounting of thermocouples in a large slab.

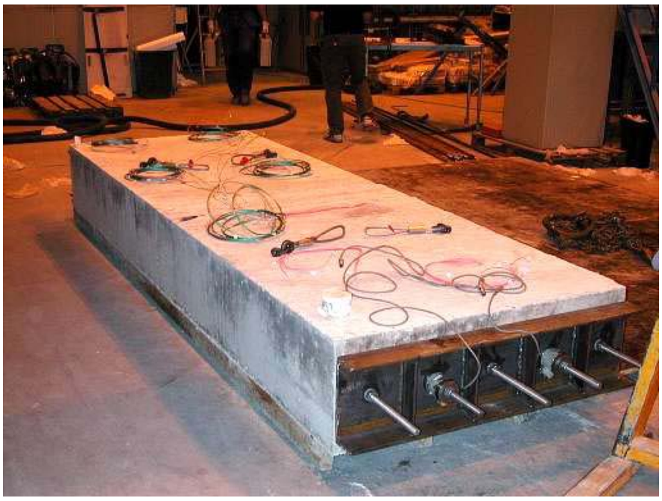

Figure F3. Two large slabs coupled with pre-stress bars.

Figure F4. Close-up on load cell.

Figure F5. Stiffened steel beam for transferring load to the specimen.

Figure F6. Mounting of specimens on the furnace.

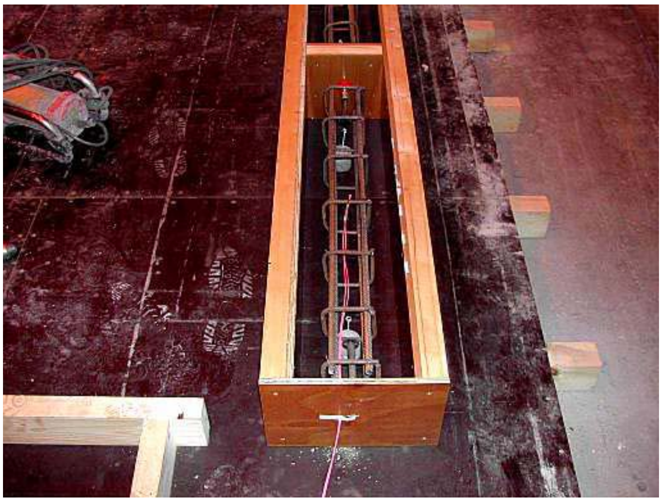

Figure F7. Reinforcement of column.

Figure F8. Columns mounted in the furnace.

Figure F9. Mould for small slabs.

Figure F10. Cylinders on the floor of the furnace.

Figure F11. Small slabs and cubes of the floor of the furnace.

Figure F12. Insulation of furnace walls.

F2 - Specimens after fire tests

Specimen A1

Figure F13. Specimen A1.

Figure F14. Specimen A1.

Figure F15. Specimen A1.

Figure F16. Specimen A1.

Figure F17. Specimen A1.

Figure F18. Specimen A1.

Figure F19. Specimen A1.

Figure F20. Specimen A1.

Figure F21. Specimen A1.

Figure F22. Specimen A1.

Figure F23. Specimen A1.

Specimen A2

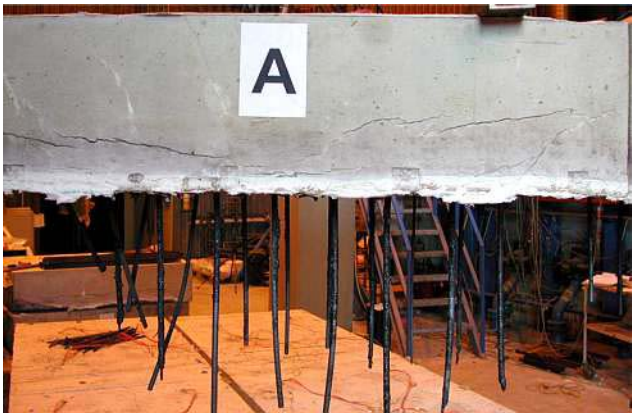

Figure F24. Specimen A2.

Figure F25. Specimen A2.

Figure F26. Specimen A2.

Figure F27. Specimen A2.

Figure F28. Specimen A2.

Figure F29. Specimen A2.

Figure F30. Specimen A2.

Figure F31. Specimen A2.

Figure F32. Specimen A2.

Figure F33. Specimen A2.

Specimen B1

Figure F34. Specimen B1.

Figure F35. Specimen B1.

Figure F36. Specimen B1.

Figure F37. Specimen B1.

Figure F38. Specimen B1.

Figure F39. Specimen B1.

Figure F40. Specimen B1.

Figure F41. Specimen B1.

Specimen B2

Figure F42. Specimen B2.

Figure F43. Specimen B2.

Figure F44. Specimen B2.

Figure F45. Specimen B2.

Specimen C1

Figure F46. Specimen C1.

Figure F47. Specimen C1.

Figure F48. Specimen C1.

Figure F49. Specimen C1.

Figure F50. Specimen C1.

Figure F51. Specimen C1.

Figure F52. Specimen C1.

Figure F53. Specimen C1.

Figure F54. Specimen C1.

Figure F55. Specimen C1.

Figure F56. Specimen C1.

Specimen C2

Figure F57. Specimen C2.

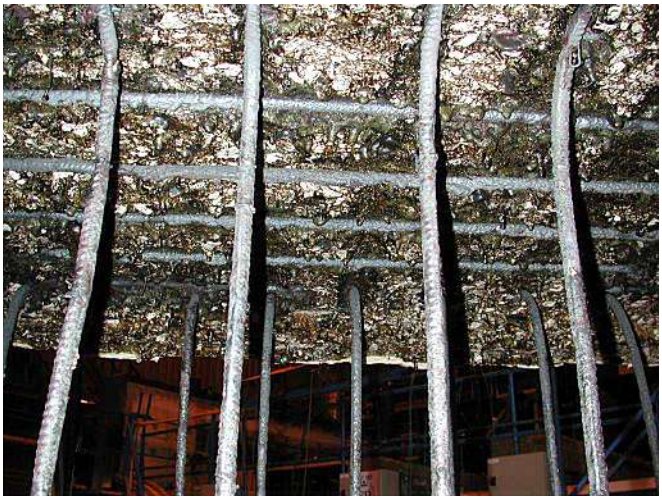
Figure F58. Specimen C2.


Figure F59. Specimen C2.

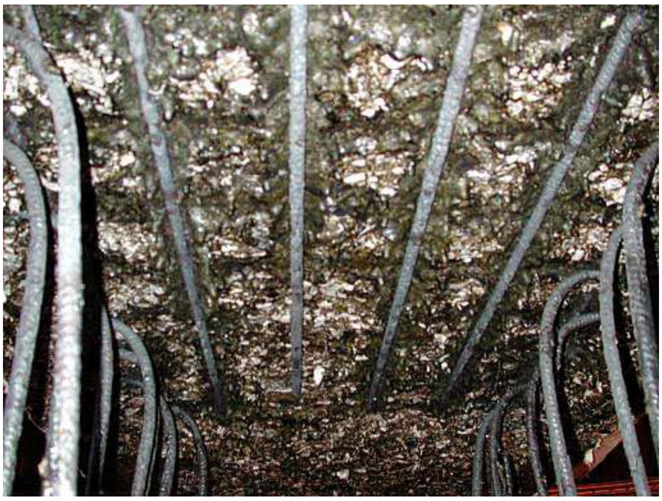

Figure F60. Specimen C2.

Figure F61. Specimen C2.

Figure F62. Specimen C2.


Figure F63. Specimen C2.


Figure F64. Specimen C2.


Figure F65. Specimen C2.

Figure F66. Specimen C2.

Specimen D1

Figure F67. Specimen D1.

Figure F68. Specimen D1.

Figure F69. Specimen D1.

Figure F70. Specimen D1.

Figure F71. Specimen D1.

Figure F72. Specimen D1.

Specimen D2

Figure F73. Specimen D2.

Figure F74. Specimen D2.

Specimen E1

Figure F75. Specimen E1.

Figure F76. Specimen E1.

Figure F77. Specimen E1.

Figure F78. Specimen E1.

Figure F79. Specimen E1.

Figure F80. Specimen E1.

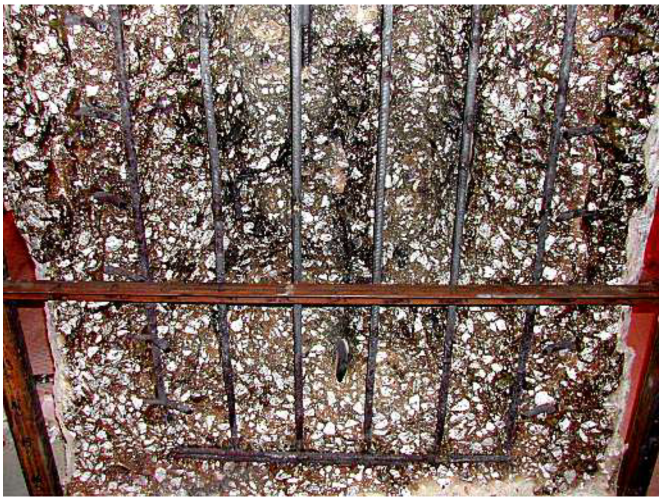

Figure F81. Specimen E1.

Figure F82. Specimen E1.

Figure F83. Specimen E1.

Figure F84. Specimen E1.

Figure F85. Specimen E1.

Figure F86. Specimen E1.

Specimen E2

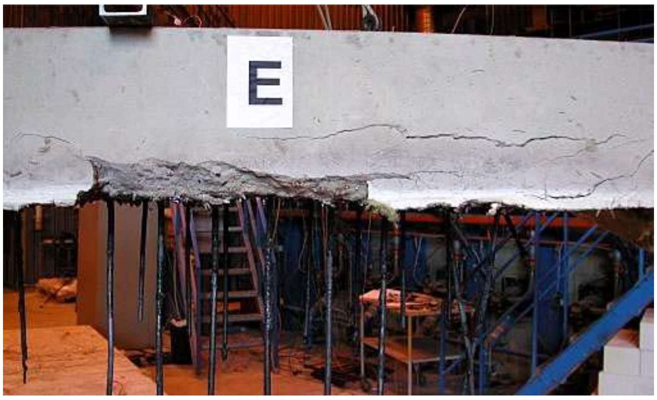

Figure F87. Specimen E2.


Figure F88. Specimen E2.


Figure F89. Specimen E2.

Figure F90. Specimen E2.

Figure F91. Specimen E2.

Figure F92. Specimen E2.

Figure F93. Specimen E2.

Figure F94. Specimen E2.

Figure F95. Specimen E2.


Figure F96. Specimen E2.


Figure F97. Specimen E2.


Figure F98. Specimen E2.

Specimen F1

Figure F99. Specimen F1.

Figure F100. Specimen F1.

Figure F101. Specimen F1.

Figure F102. Specimen F1.

Figure F103. Specimen F1.

Figure F104. Specimen F1.

Figure F105. Specimen F1.

Figure F106. Specimen F1.

Figure F107. Specimen F1.

Specimen F2

Figure F108. Specimen F2.

Figure F109. Specimen F2.

Figure F110. Specimen F2.

Figure F111. Specimen F2.

Figure F112. Specimen F2.

Columns after first fire test

Figure F113. Columns after the first fire test. From the left: A10, C10, D10.

Figure F114. Columns after the first fire test. From the left: A10, C10, D10.

Figure F115. Columns after the first fire test. From the left: A10, C10, D10.

Figure F116. Columns after the first fire test. From the left: A10, C10.

Columns after the second fire test

Concrete A

Figure F117. Column A11.

Figure F118. Column A11.

Figure F119. Column A11.

Figure F120. Column A11.

Figure F121. Column A11.

Concrete C

Figure F122. Column C11.

Figure F123. Column C11.

Figure F124. Column C11.

Figure F125. Column C11.

Figure F126. Column C11.

Concrete D

Figure F127. Column D11.

Figure F128. Column D11.

Figure F129. Column D11.

Figure F130. Column D11.

Figure F131. Column D11.

Figure F132. Column D11.

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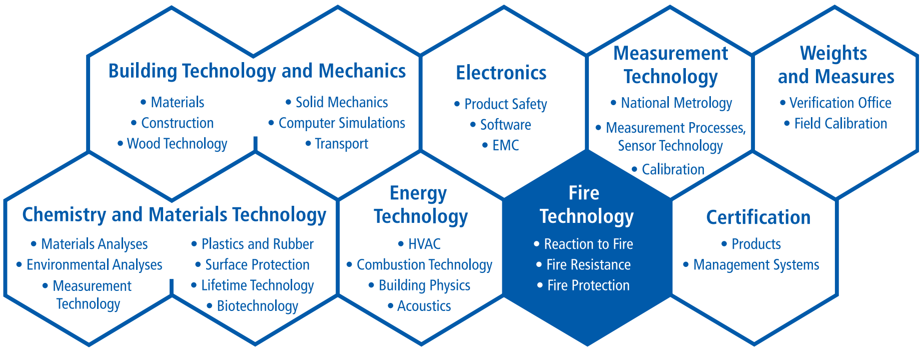

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