Lars Boström

The Performance of Some Self Compacting Concretes When Exposed to Fire

SP Swedish National Testing and Research Institute

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Abstract

The objective with the study was to examine the behaviour of self compacting concrete when exposed to fire and compare the results with those of normal concrete. Twelve different types of self compacting concretes as well as four different conventional vibrated concretes have been fire tested.

The results from the study showed that the examined self compacting concretes got explosive spalling if no precaution such as polypropylene fibres was used. By adding polypropylene fibres in the admixture the amount of spalling could be reduced and the same level of spalling as that for normal concrete was achieved.

When comparing concrete with glass filler and limestone filler the latter spalled more. If this is due to different water-powder ratio or the filler material is not clear. The results indicate a linear relation between the amount of spalling and the water-powder ratio.

Since the study was very limited in the amount of test material and the very extensive spalling obtained, it is important to continue the research on the behaviour of self compacting concrete when exposed to fire. It is difficult to draw any conclusions from this study on how to manufacture self compacting concrete to obtain a certain fire resistance. Nevertheless, the investigation show that it is possible by for example using polypropylene fibres to produce self compacting concrete with behaviour similar to that of conventional vibrated concrete.

Key words: self compacting concrete, high temperature, fire, spalling

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Preface

This work was initiated and financial supported by the Development Fund of the Swedish Construction Industry (SBUF), the Swedish Fire Research Board (Brandforsk) and Skanska Prefab Ltd 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.

This report deals with full scale tests which is a part in a larger project where also Lund Institute of Technology, department of Building Materials, is participating.

Finally thanks to the following persons who have been, more or less, involved in the project group and helped with valuable comments:

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Summary

As part of a larger project focused on the behaviour of self compacting concrete at elevated temperatures have full scale tests been performed on different concretes. A total of twelve different qualities of self compacting concretes as well as four different qualities of conventional vibrated concrete have been tested. Four self compacting concretes and one normal concrete were tested with a more severe fire exposure defined by the HC-curve. All other concretes were tested with the standard time-temperature relation in accordance with EN 1363-1 (ISO 834).

Two different fillers, glass and limestone powder, where examined as well as different amount of polypropylene fibres in the self compacting concrete. All specimens had the same square geometry with the dimensions 200 x 200 x 2000 mm, and they were all pre-stressed. The specimens were fire tested in a horizontal furnace, where they were hanging from a roof structure above the furnace. The duration of the fire tests were 90 minutes.

The test specimens were manufactured by Skanska Prefab Ltd in the factory located at Bollebygd, Sweden. They were manufactured six months before testing. Thirteen of the test specimens were made using Degerhamn Standard cement and stored under water until testing. The remaining test specimens were made using Skövde Bygg cement and conditioned in air at 20 °C and 50 % relative humidity. Shortly before the fire tests the relative humidity in some of the test specimens were measured.

In order to determine the amount of spalling the test specimens were weighted before and after the fire tests. The amount of spalling were then calculated as the material loss due to the fire exposure divided with the weight of the specimen before the test. In the calculation an estimated weight of water was subtracted.

Before casting the concrete a total of ten thermocouples were mounted in the mould at different locations. Thus was the temperature measured in the specimens during the fire tests.

During the fire tests some of the specimens showed explosive and extensive spalling. Although, it was clear that by using polypropylene the amount of spalling could be decreased. According to these tests, with the admixtures used, self compacting concrete with limestone powder spalled more than the ones with glass powder. It is not clear if the type of filler is the reason or if it is the amount of filler. The results also showed that for the concretes without fibres there is a linear relation between the amount of spalling and the water-powder ratio. The water-powder ratio is the ratio between the mass of water and the combined mass of cement and filler.

1 Introduction

1.1 Background

Self compacting concrete (SCC) has during the last years been introduced to the market. The main advantage with self compacting concrete compared to conventional concrete is that no energy is required to compact the concrete so the reinforcement is covered or the mould is filled out. Thus no vibration is needed for self compacting concrete.

The characteristics and behaviour of self compacting concrete has been studied in several projects around the world and is presently well known. There is, however, very little information on the behaviour of self compacting concrete when exposed to fire. Since the composition of self compacting concrete is different from that of conventional concrete it may act differently in a fire situation. Therefore it is of great importance that the behaviour in transient high temperature conditions is investigated.

1.2 Previous studies

In a study by Blontrock and Taerwe, small cylinders (diameter 150 mm and length 300 mm) of three different self compacting concretes and on conventional concrete were fire tested [1]. The specimens were unloaded and only minor spalling could be observed. The results from their study were that the degree of spalling depends on the type of filler and on the moisture content when tested.

Another test series was carried out by CERIB [4] where rectangular reinforced elements were tested. The size of the elements were 200 x 300 x 650 mm and 300 x 500 x 700 mm. The test specimens were unloaded during the fire tests. This study resulted in minor spalling which did not differ much from the spalling of conventional concrete.

1.3 Objectives

The objectives of the present study were to investigate the performance of some different self compacting concretes and to compare these with conventional vibrated concrete when exposed to fire.

1.4 Limitations

A total of sixteen different concretes were studied in the full scale tests. Of these were four conventional vibrated concretes and the remaining twelve were self compacting concretes. It should be noted that it is possible to manufacture self compacting concrete with other recipes than the one used and thus obtain other behaviour than the ones obtained in the present study.

The full scale tests were carried out on relative small test specimens which were tested as columns in the furnace, i.e. a four-sided fire exposure. All test specimens had the same geometry, 0.2 x 0.2 x 2.0 m. The only mechanical load used was the pre-stressing of the columns.

2 Materials

A total of 40 test specimens were manufactured at Skanska Prefab AB in Bollebygd. The different concretes are summarized in Table 2.1, which also gives the number of specimens of each concrete. All test specimens were pre-stressed but the load level applied was not the same for all specimens. In the tests 16 different concretes were used of which 12 were self compacting and the remaining four were conventional vibrated concretes. Two different cements were used, Degerhamn Standard and Skövde Bygg. An explanation to the code for specimen type is as follows;

Example: 40AK2
40 - w/c-ratio (40 = 0.40, 55 = 0.55, 70 = 0.70)
A - Cement (A = Degerhamn Standard, B = Skövde Bygg)
K - Filler type (K = lime powder, G = glass powder, R = no filler)
2 - Amount of fibres (0 = no fibres, 2 = 2 kg fibres/m^3 concrete, 4 = 4 kg fibres/m^3 concrete)

A more throughout description and explanation of the different concretes will be given in a report by Persson [3].

Table 2.1 Summary of test specimens used in furnace tests.

Specimen type	Number of spec.	w/c-ratio	Cement	Filler	Fibres kg/m^3	Pre-stress	Fire curve
40AK0	3	0.40	Degerhamn Standard*	Lime	-	112 kN	HC-curve
40AK2	3	0.40	Degerhamn Standard*	Lime	2	112 kN	HC-curve
40AK4	2	0.40	Degerhamn Standard*	Lime	4	112 kN	HC-curve
40AG0	3	0.40	Degerhamn Standard*	Glass	-	112 kN	HC-curve
40AR0	2	0.40	Degerhamn Standard*	-	-	112 kN	HC-curve
40BK0	3	0.40	Skövde Bygg**	Lime	-	112 kN	Std-curve
40BR0	2	0.40	Skövde Bygg**	-	-	112 kN	Std-curve
55BK0	2	0.55	Skövde Bygg**	Lime	-	122 kN	Std-curve
55BK2	2	0.55	Skövde Bygg**	Lime	2	122 kN	Std-curve
55BK4	2	0.55	Skövde Bygg**	Lime	4	122 kN	Std-curve
55BR0	2	0.55	Skövde Bygg**	-	-	122 kN	Std-curve
70BK0	3	0.70	Skövde Bygg**	Lime	-	104 kN	Std-curve
70BK2	3	0.70	Skövde Bygg**	Lime	2	104 kN	Std-curve
70BK4	3	0.70	Skövde Bygg**	Lime	4	104 kN	Std-curve
70BG0	3	0.70	Skövde Bygg**	Glass	-	104 kN	Std-curve
70BR0	2	0.70	Skövde Bygg**	-	-	104 kN	Std-curve

* CEM I 42,5 BV/SR/LA
** CEM II/A-LL 42,5R

After casting the test specimens were stored for six months before the fire tests. The specimens made of concrete with Degerhamn Standard cement were all stored under water, while all other specimens were stored in air with a climate of 20 °C and 50 % relative humidity. The mix proportions of the concretes are presented in Appendix C. The design of the test specimens is shown in figure 2.1.

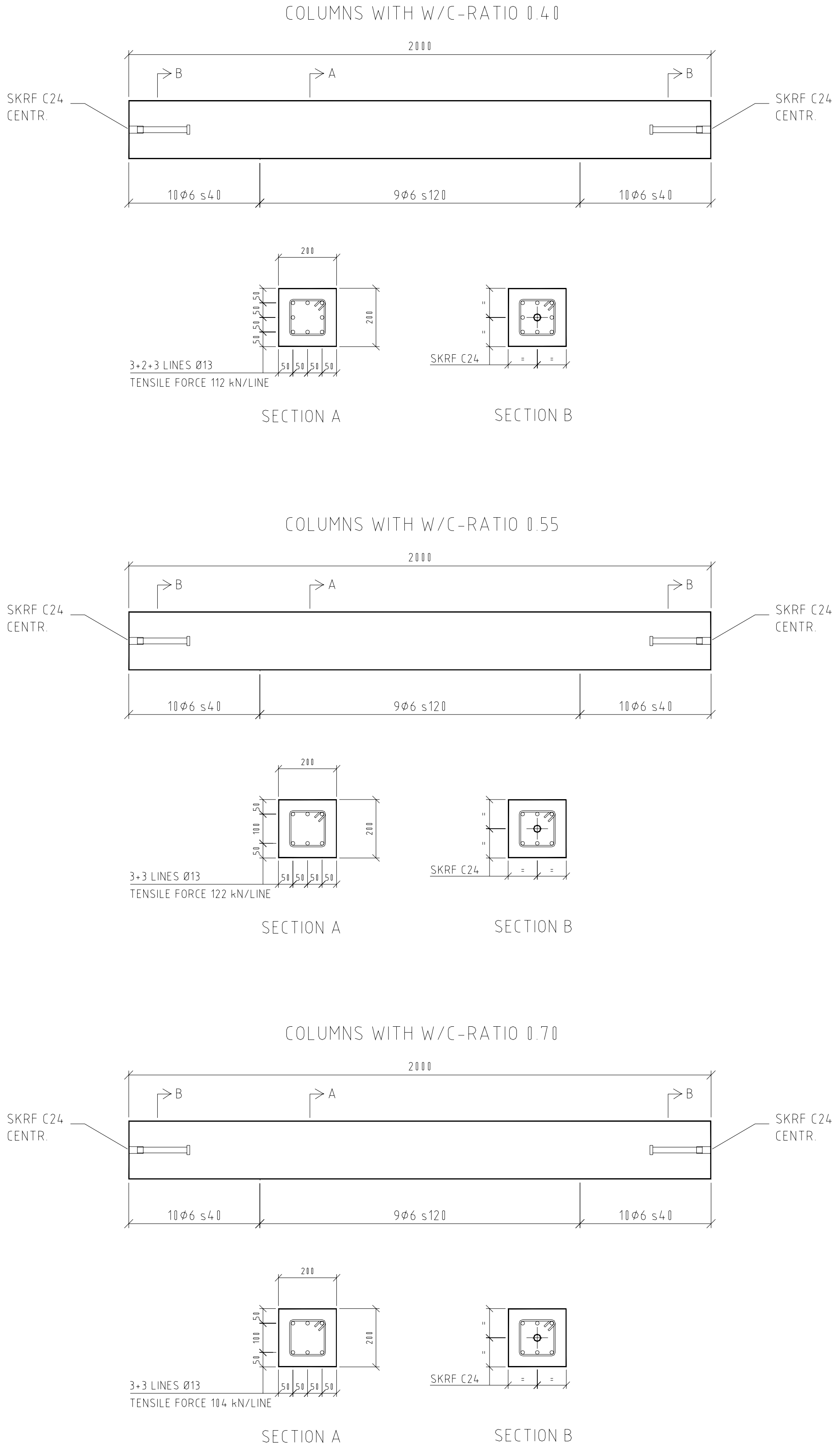

Figure 2.1 Design of test specimens.

3 Measurements

3.1 Density

The density of the test specimens have been determined from the weight and the nominal dimensions of the test specimens before the test, i.e. the density including water. The weight of the test specimens were measured by hanging the specimen in a load cell. The weight of the iron works used between the load cell and the test specimen used in order to attach them together, was subtracted from the total weight. The weight of the reinforcement steel as well as the water content was included in the density. The dimensions used for calculating density was for all specimens 200 x 200 x 2000 mm.

3.2 Relative humidity in test specimens

Shortly before the fire testing the relative humidity within the test specimens were measured in nine of the test specimens. A hole was drilled with a depth of 100 mm in each of the selected test specimens. In each hole a moisture sensor, designated Vaisala HMP, was inserted. The space between the surface of the concrete and the sensor was sealed. The relative humidity in the hole was measured during 5 days, after which the relative humidity had stabilised.

3.3 Furnace tests

All tests were carried out in accordance with EN 1363-1. The test specimens were hanging from concrete plates which were covering the furnace. In two of the fire tests 13 test specimens were placed in the furnace, and in the third fire test 14 test specimens were placed in the furnace. The placement of the columns in the furnace are shown in figures 3.1-2 and in Table 3.1. Figure 3.3 shows a photo of some columns in the furnace.

The columns were hanging from a 200 mm thick concrete deck which was placed on top of the horizontal furnace. The columns were hanging in a bolt. Between the test specimens and the concrete deck was an insulation attached consisting of two layers of 25 mm thick ceramic fibre. At the bottom of the columns was also an insulation attached consisting of one 25 mm ceramic fibre closest to the test specimen and outside this a 50 mm thick rock wool insulation with a nominal density of 150 kg/m^3. The insulation was kept in place by a 100 mm long piece of UNP100 steel profile. The complete insulation system under the columns were hanging in a M24 bolt which was screwed into the test specimen.

The columns were symmetrically placed within the furnace with a closest distance of 250 mm between two adjacent corners of the columns. The columns closest to the furnace walls were located 350 mm from the wall.

Test 1, which included all specimens made with cement designated Degerhamn Standard and stored in water, was controlled in accordance with the hydrocarbon curve (HC-curve) given in EN 1363-2. This time-temperature curve is more severe than the standard curve. It is used for applications where more severe fires may be expected such as for the petrochemical industry, offshore oil industries or tunnels where very intense fires such as liquid pool fires may occur.

Test 2 and test 3 were controlled in accordance with the standard time-temperature curve given in EN 1363-1, i.e. similar to ISO 834. The different time-temperature curves are shown in figure 3.4. In all tests the burners, except 2, 5, 8 and 11 as shown in figure 3.2, were used. Thus there were no flames directly on the test specimens.

Table 3.1 Placement of columns in the furnace.

Column	Test 1 April 16, 2002	Test 2 April 23, 2002	Test 3 April 29, 2002
A	40AK0 - spec. 1	40BK0 - spec. 1	70BK0 - spec. 1
B	40AK2 - spec. 1	40BR0 - spec. 1	70BK2 - spec. 1
C	40AK4 - spec. 1	55BK0 - spec. 1	70BK4 - spec. 1
D	40AG0 - spec. 1	55BK2 - spec. 1	70BG0 - spec. 1
E	40AR0 - spec. 1	55BK4 - spec. 1	70BR0 - spec. 1
F	40AK0 - spec. 2	55BR0 - spec. 1	70BK0 - spec. 2
G	40AK2 - spec. 2	40BK0 - spec. 2	70BK2 - spec. 2
H	40AK4 - spec. 2	40BR0 - spec. 2	70BK4 - spec. 2
I	40AG0 - spec. 2	55BK0 - spec. 2	70BG0 - spec. 2
J	40AR0 - spec. 2	55BK2 - spec. 2	70BR0 - spec. 2
K	40AK0 - spec. 3	55BK4 - spec. 2	70BK0 - spec. 3
L	40AK2 - spec. 3	55BR0 - spec. 2	70BK2 - spec. 3
M	40AG0 - spec. 3	40BK0 - spec. 3	70BK4 - spec. 3
N	-	-	70BG0 - spec. 3

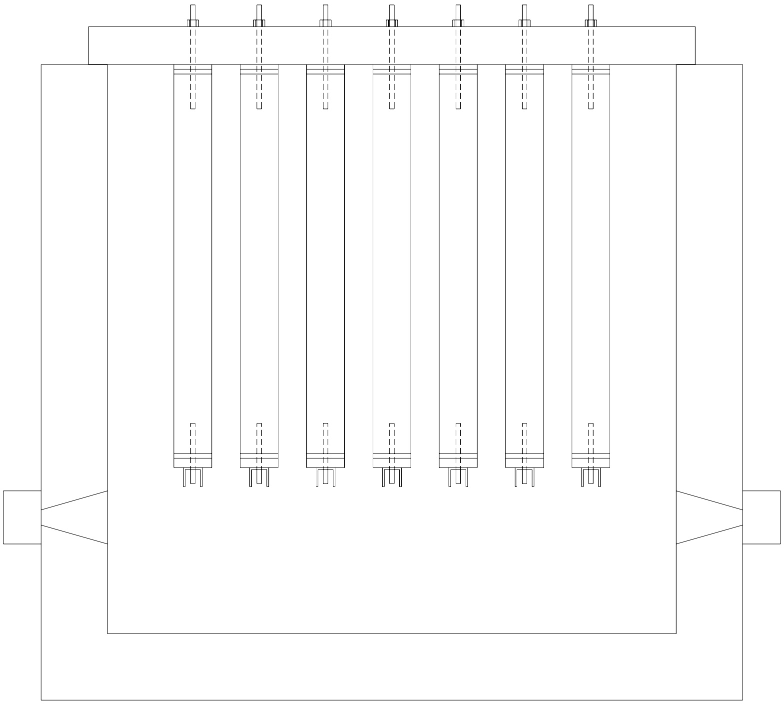

Figure 3.1 Columns in the furnace. Section view from the south.

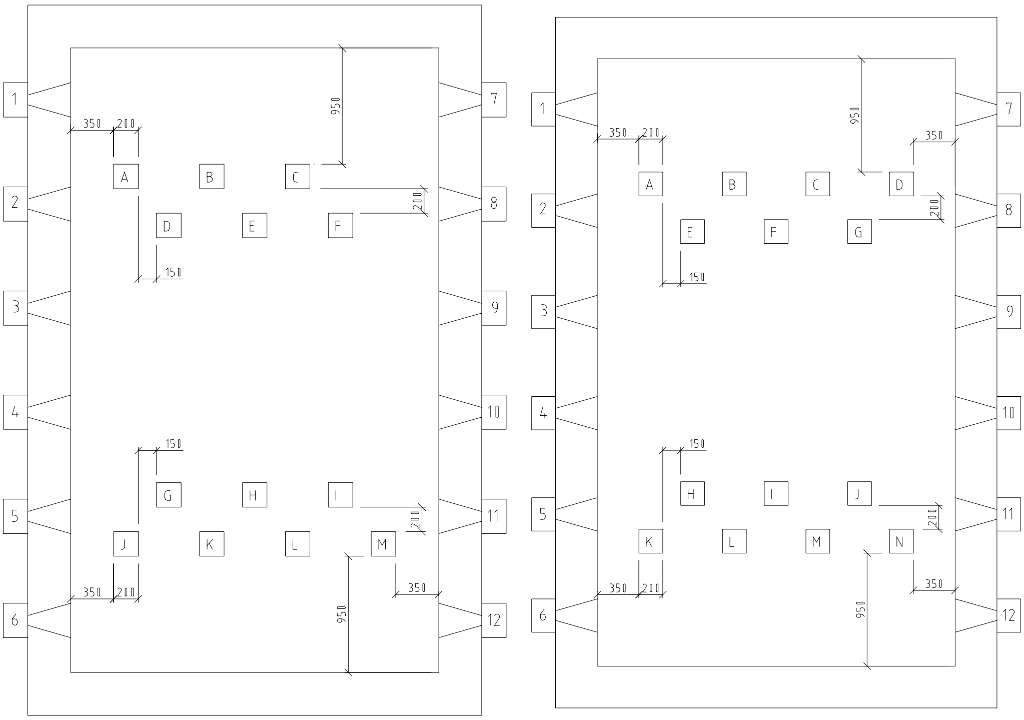

Figure 3.2 Placement of columns in the furnace. Test 1 and 2 at the left and test 3 at the right.

Figure 3.3 Test specimens in the furnace before test.

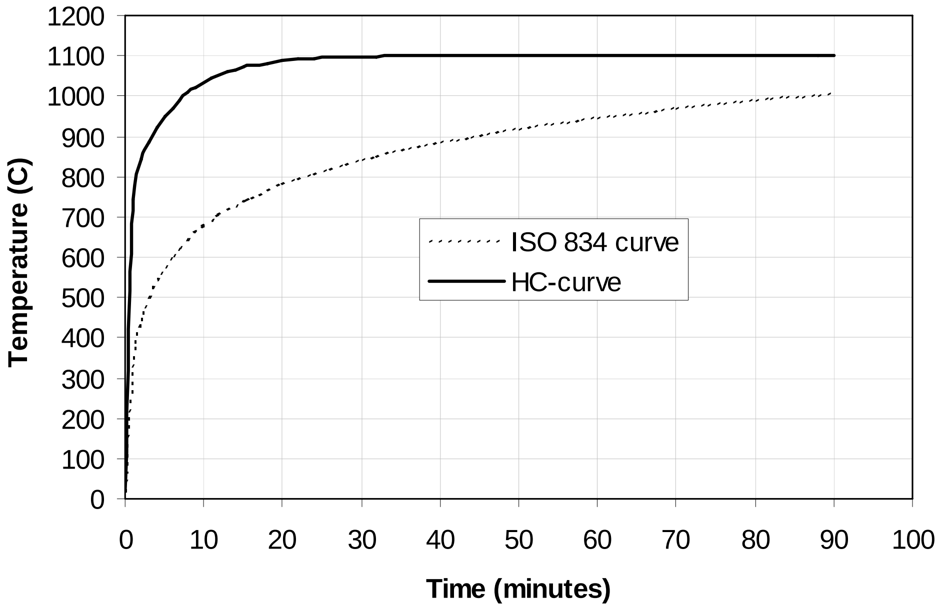

Figure 3.4 Different time-temperature curves used in the furnace tests.

The pressure in the furnace in relation to the ambient pressure in the laboratory hall was kept constant during all three tests. The pressure difference between the furnace and the laboratory hall was 18 Pa at a level 250 mm below the concrete deck.

The temperature in the furnace was measured by means of plate thermocouples, as prescribed in EN 1363-1. The location of the plate thermocouples is shown in figures 3.5-6. The plate thermometers were directed with the steel surface in the direction showed in the figures. All plate thermocouples except PT18-PT20 in test 1 and 2, and PT19-PT20 in test 3, were located 550 mm below the concrete deck, i.e. 500 mm below the top of the test specimens. Plate thermocouples PT18-PT20 in test 1 and 2, and PT19-PT20 in test 3, were located 1550 mm below the concrete deck, i.e. 500 mm above the bottom of the test specimens. All plate thermocouples were placed 100 mm from the surface of the test specimens.

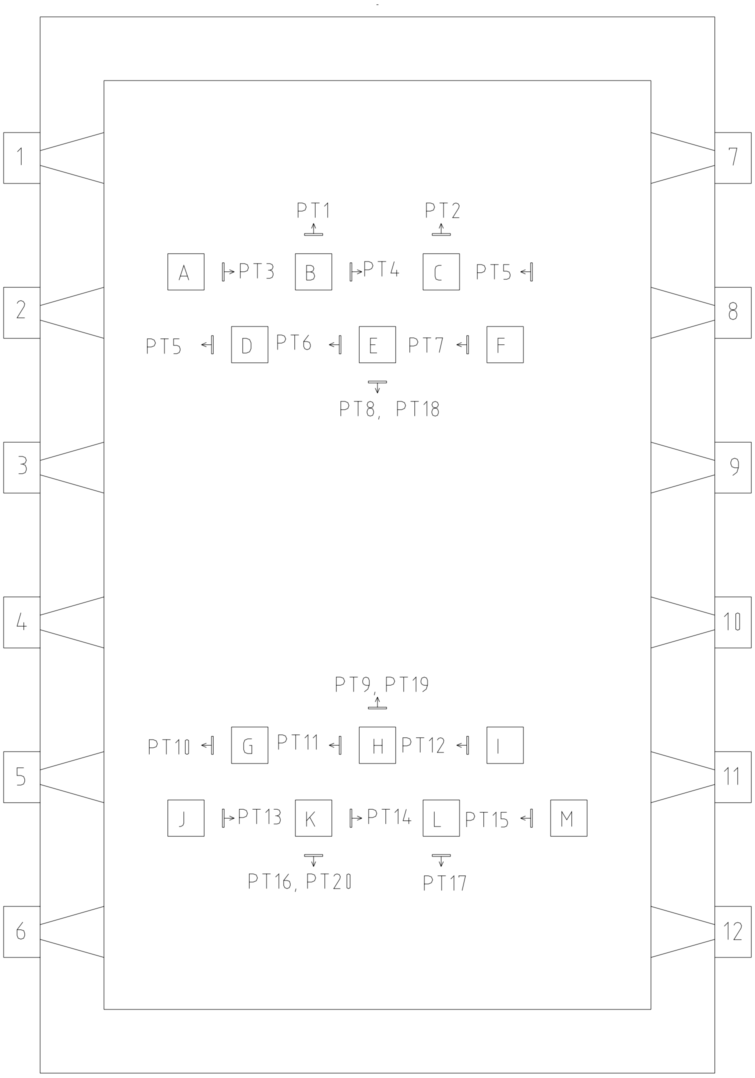

Figure 3.5 Location of plate thermocouples in test 1 and test 2.

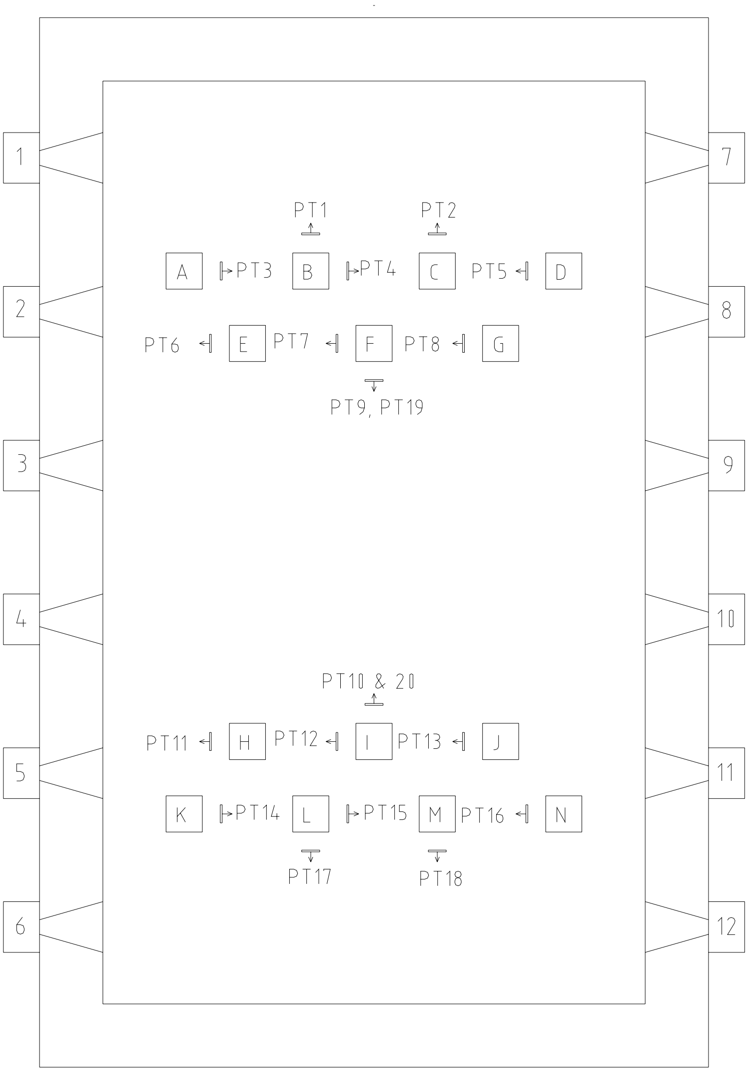

Figure 3.6 Location of plate thermocouples in test 3.

3.4 Measurement of spalling

Before the furnace test the columns were weighted with a load cell. The specimens were lifted with a crane and a load cell was attached between the specimen and the hook of the crane. The weight of the mechanical joints between the specimen and the load cell was subtracted from the reed load.

One day after the fire test, i.e. when the columns had cooled down to a temperature so they could be handled, the weight was measured once more. The weight was also measured between one and three weeks after the fire test in order to determine the amount of material loosening when stored for a short while after the fire.

The concrete contains water which migrates out of the specimens during the fire test. It has not been possible to exactly determine how much of the water was lost during the fire test. It has been estimated that the concrete stored in water, which was in equilibrium with 90 % relative humidity, contained 100 kg water per m^3 concrete. The concrete stored in air, which was in equilibrium with 75 % relative humidity, was estimated to contain 70 kg water per m^3 concrete. When calculating the weight loss due to spalling it was assumed that all this water migrated out of the specimens.

The weight of the polypropylene fibres included in some of the test specimens has also been subtracted from the weight because they are supposed to disappear during the fire test.

The weight loss due to spalling was calculated as

$$spalling = \frac{m_{specimen\ before\ test} - m_{water} - m_{fibres} - m_{specimen\ after\ test}}{m_{specimen\ before\ test} - m_{water}}$$

where $spalling$ is the percentage weight loss due to spalling
$m_{specimen\ before\ test}$ is the weight of the specimen before the fire test
m_{water} is the approximated weight of the migrated water
m_{fibres} is the weight of polypropylene fibres
$m_{specimen\ after\ test}$ is the weight of the specimen after the fire test

3.5 Temperature in the concrete

The temperature in the concrete has been measured with thermocouples type K during the fire test. At the end of the wire a quick-tip was mounted on each thermocouple, see figure 3.7. The wire was also protected by using shrinking tubing on top of the wires normal insulation. The thermocouples were mounted at different depths and locations within the specimen. In each test specimen ten thermocouples were mounted, six thermocouples 500 mm below the top and four thermocouples 1500 mm from the top. A total of 130 thermocouples were used during test 1 and 2, and 140 thermocouples during test 3. Figure 3.8 show the location of the thermocouples.

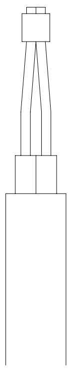

Figure 3.7 Thermocouple with quick-tip at the top and shrinking tube on the insulation.

During the form stripping some of the thermocouple wires were cut. It was not possible to repair the wires since they were cut very close to the concrete surface. Thus some temperature measurements are missing in the results.

The thermocouples were attached to a data acquisition equipment and measurements were collected every fifth second during the whole test.

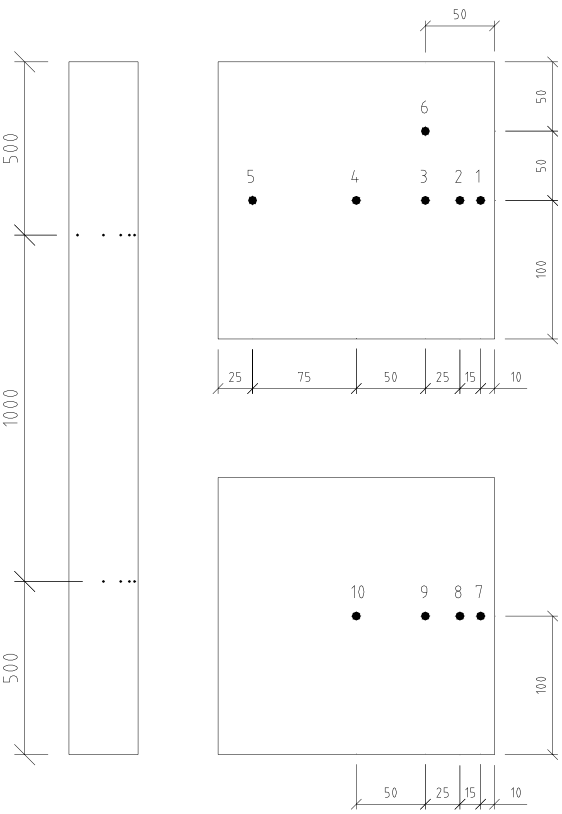

Figure 3.8 Location of thermocouples within the test specimens.

4 Results

4.1 Density

The density measurements were only made to get the nominal density of the tested columns. The density given is calculated from the nominal dimensions of the columns and the weight before the furnace test, i.e. the weight include the weight of the reinforcement steel. Table 4.1 show the determined densities and the coefficient of variation (σ/m).

Table 4.1 Density of the tested material.

Concrete	Density	
	Mean (kg/m^3)	C.o.V. (%)
40AK0	2650	0.2
40AK2	2640	1.2
40AK4	2640	0.3
40AG0	2630	0.8
40AR0	2630	0.3
40BK0	2600	0.3
40BR0	2660	1.2
55BK0	2530	0.4
55BK2	2570	0.6
55BK4	2510	0.2
55BR0	2540	0.6
70BK0	2520	0.6
70BK2	2470	0.3
70BK4	2450	1.0
70BG0	2470	0.7
70BR0	2460	0.7

4.2 Water content

The water content of the concrete before the furnace tests could not be directly measured. Thus was the relative humidity in some of the test specimens measured before the tests. Table 4.2 show the measured relative humidity. There are no sorption isotherms available for the self compacting concrete and thus the amount of water in the self compacting concrete cannot be determined from the relative humidity measurements. Although, an estimate has been done outgoing from the sorption isotherms for high performance concrete. For the reference concretes sorption isotherms from Nevander and Elmarsson [2] have been used and the water content calculated.

The water content has been approximated to 100 kg/m^3 for the concrete with Degerhamn Standard cement which was in equilibrium with 90 % relative humidity, and 70 kg/m^3 for the concrete with Skövde Bygg cement which was in equilibrium with 75 % relative humidity.

Table 4.2 Relative humidity in the concrete.

Material	Relative humidity
40AK0	89 %
40AG0	89 %
40AR0	93 %
40BK0	73 %
55BK0	77 %
55BR0	73 %
70BK0	76 %
70BG0	77 %
70BR0	77 %

4.3 Furnace conditions

4.3.1 Test series 1 - EN 1363-2 Hydrocarbon fire

The first test series was controlled in accordance with the hydrocarbon curve (HC-curve) described in EN 1363-2. The control was kept on all 20 plate thermocouples except for a period between 25 minutes and 70 minutes where plate thermocouple PT2 was not functioning correctly. The measured mean temperature in the furnace as well as the prescribed HC-curve are shown in figure 4.1. The temperature of each plate thermocouple is shown in figure 4.2.

It was not possible to reach the required temperature during the first 50 minutes. The start up to about 3 minutes worked well, but thereafter the temperature could not keep up with the required temperatures. The reason for this is the large amount of wet concrete in the furnace. More than 1 m^3 of concrete should be heated and a lot of water to be evaporated, which in this case was too much for the capacity of the available burners.

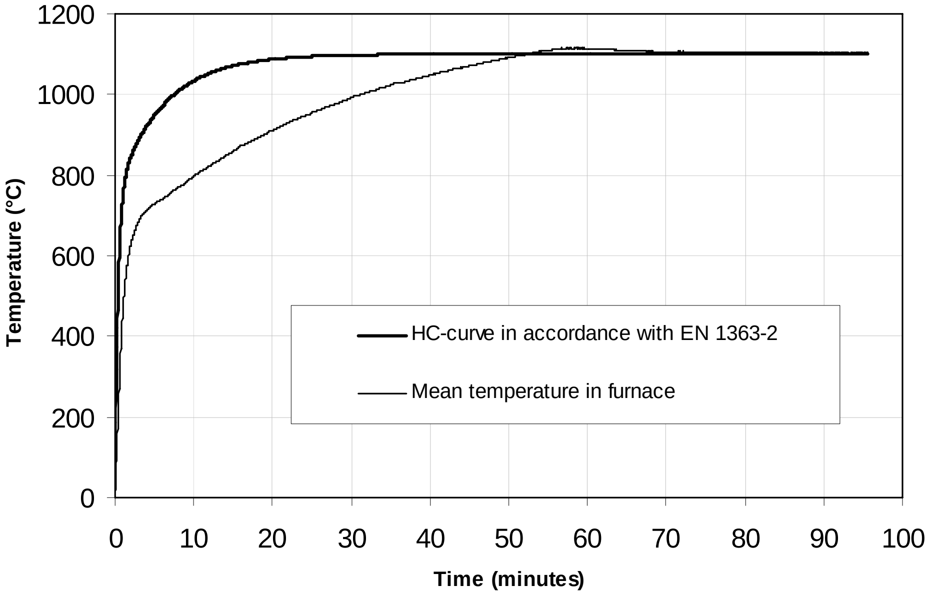

Figure 4.1 Measured mean temperature in furnace and HC-curve as prescribed in EN 1363-2.

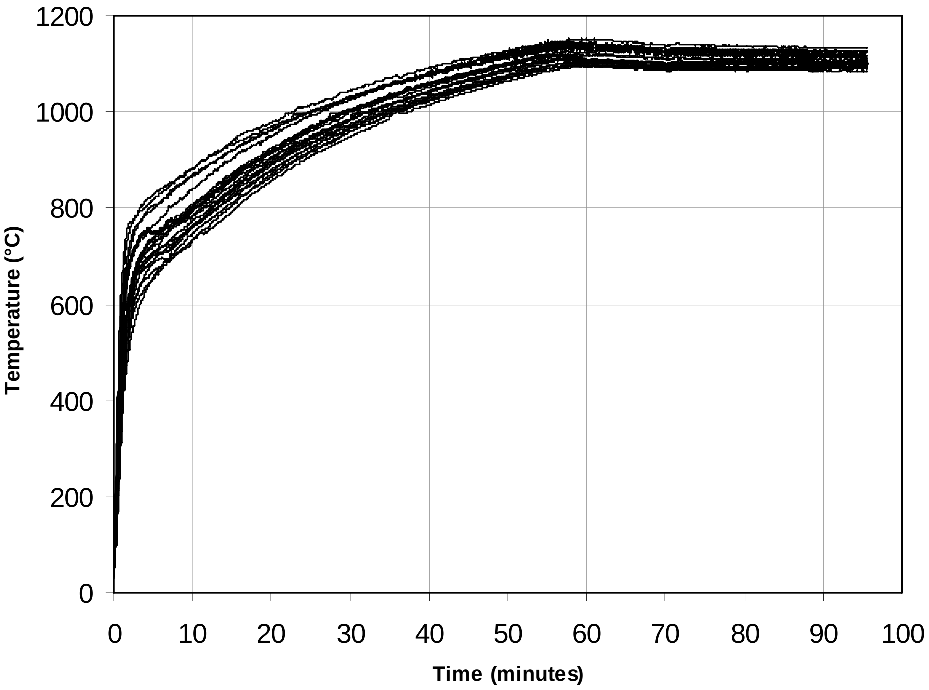

Figure 4.2 Temperature of each individual plate thermocouple. Plate thermocouple PT2 was out of function during the period between 25 minutes and 70 minutes.

The pressure in the furnace was measured with one gauge placed 250 mm below the concrete deck. The control pressure was set to 18 Pa, i.e. an overpressure in the furnace of 18 Pa compared to the laboratory hall.

The ambient temperature in the laboratory hall was measured by a thermocouple mounted outside the north wall of the furnace. The measuring device was constructed in accordance with the design given in EN 1363-1. The measured temperature in the laboratory hall was 19 ºC.

4.3.2 Test series 2 - EN 1363-1 Standard fire

The second test series was controlled in accordance with the standard time-temperature curve described in EN 1363-1, which is similar to the fire curve given in ISO 834. The control was kept on all 20 plate thermocouples. The measured mean temperature in the furnace as well as the prescribed time-temperature curve are shown in figure 4.3. The temperature of each plate thermocouple is shown in figure 4.4.

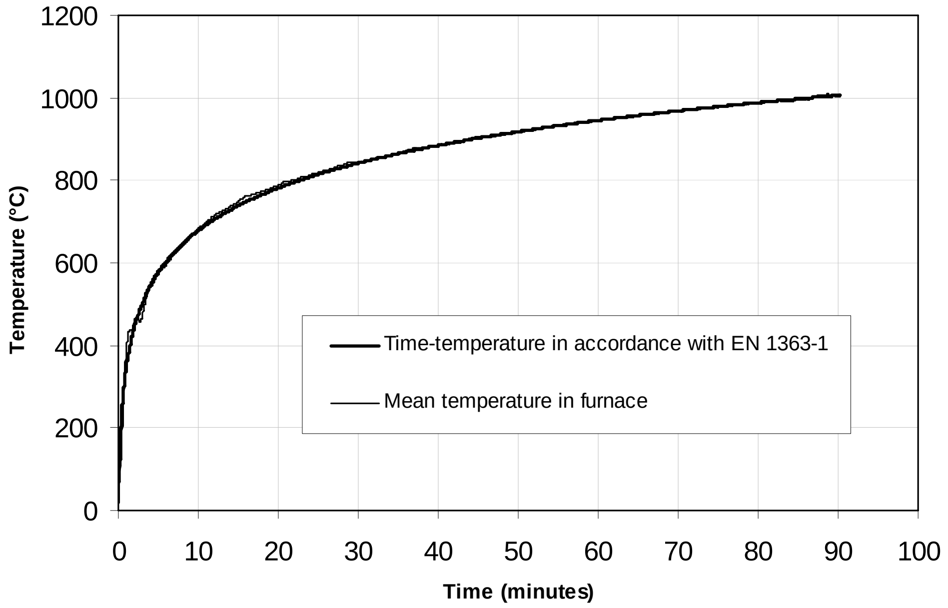

Figure 4.3 Measured mean temperature in furnace and time-temperature as prescribed in EN 1363-1.

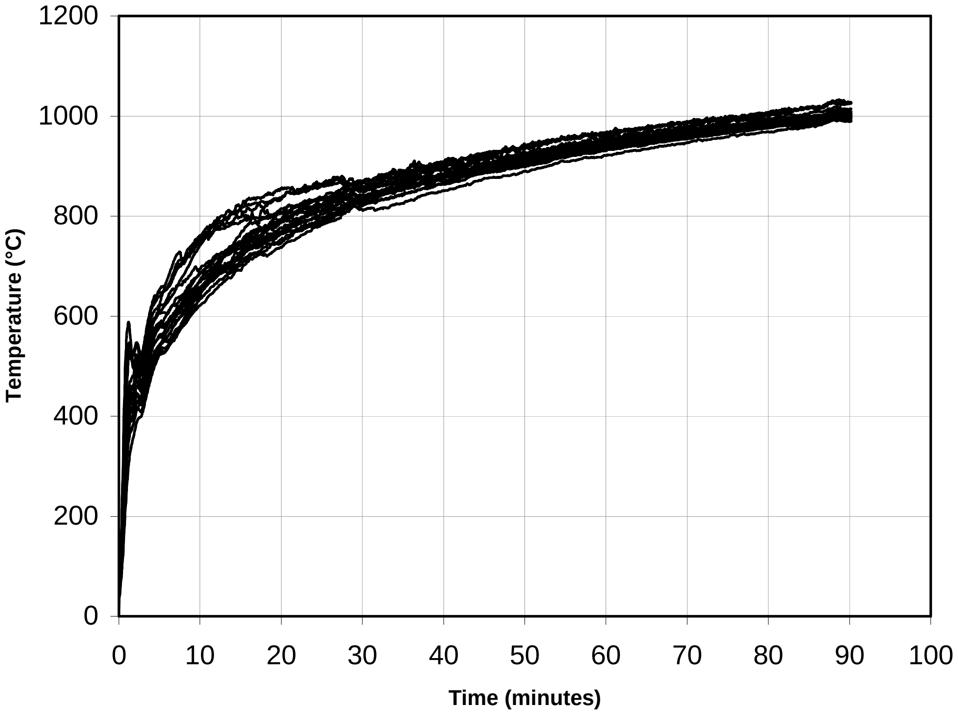

Figure 4.4 Temperature of each individual plate thermocouple.

The pressure in the furnace was measured with one gauge placed 250 mm below the concrete deck. The control pressure was set to 18 Pa, i.e. an overpressure in the furnace of 18 Pa compared to the laboratory hall.

The ambient temperature in the laboratory hall was measured by a thermocouple mounted outside the north wall of the furnace. The measuring device was constructed in accordance with the design given in EN 1363-1. The measured temperature in the laboratory hall was 20 ºC.

4.3.3 Test series 3 - EN 1363-1 Standard fire

The third test series was also controlled in accordance with the standard time-temperature curve described in EN 1363-1, i.e. a curve similar to ISO 834. The control was kept on all 20 plate thermocouples except for the first 25 minutes of the test where plate thermocouple PT20 not was functioning correctly. The measured mean temperature in the furnace as well as the prescribed time-temperature curve are shown in figure 4.5. The temperature of each plate thermocouple is shown in figure 4.6.

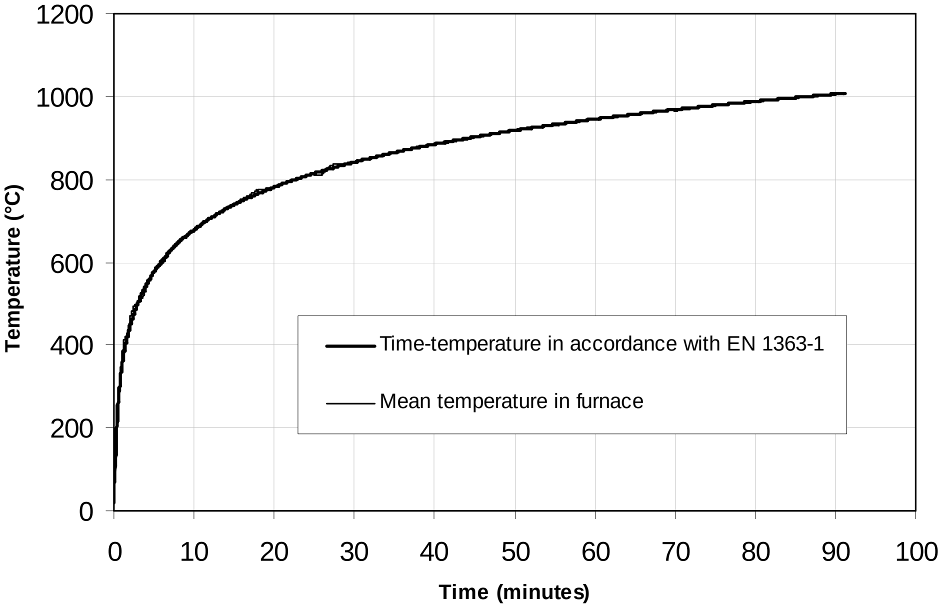

Figure 4.5 Measured mean temperature in furnace and standard time-temperature curve as prescribed in EN 1363-1.

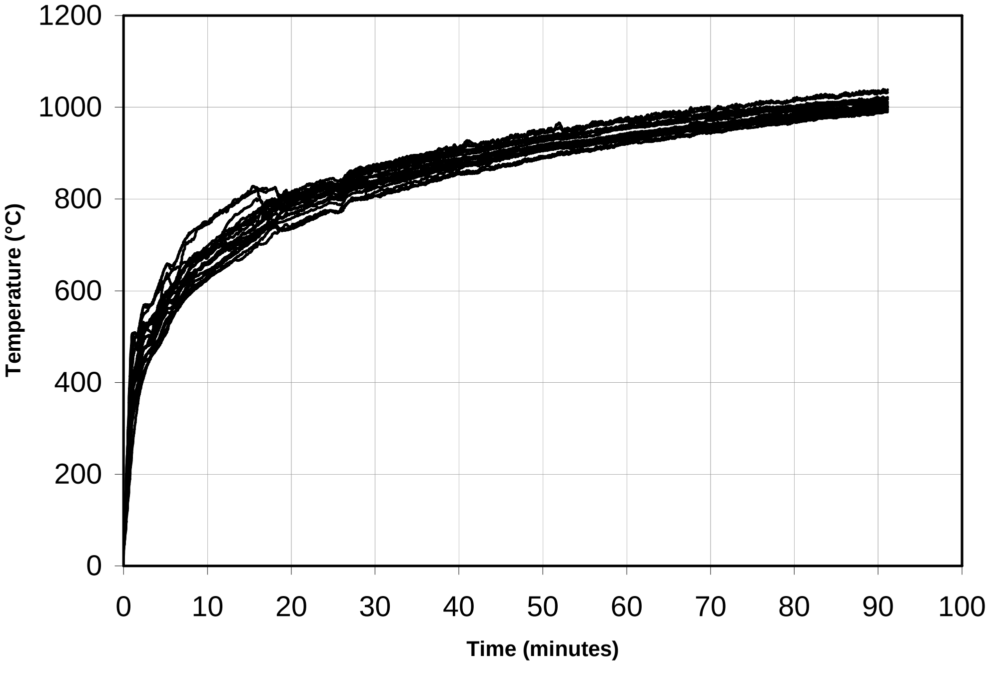

Figure 4.6 Temperature of each individual plate thermocouple. Plate thermocouple PT20 was out of function during the first 25 minutes of the test.

The pressure in the furnace was measured with one gauge placed 250 mm below the concrete deck. The control pressure was set to 18 Pa, i.e. an overpressure in the furnace of 18 Pa compared to the laboratory hall.

The ambient temperature in the laboratory hall was measured by a thermocouple mounted outside the north wall of the furnace. The measuring device was constructed in accordance with the design given in EN 1363-1. The measured temperature in the laboratory hall was 18 ºC.

4.4 Spalling

The test specimens were weighted before and after the fire test. Before weighting after the fire test all loose material was removed. The amount of spalling was calculated as the percent loss of material during the fire test, see paragraph 3.4 above. It is an estimate since it has been difficult to more exactly determine how much water the concrete contained before and after the fire test. An approximated weight of water has been assumed, and this weight was subtracted from the concrete before testing. The amount of spalling is presented in table 4.3. Since each concrete type included more than one test specimen the maximum, minimum and mean amount of spalling are shown. The amount of spalling is also shown in diagram form in figure 4.7. In addition to the w/c-ratio also the w/p-ratio is presented in table 4.3. The w/p-ratio is here defined as the ratio between the mass of water and the combined mass of cement and filler.

Table 4.3 Percentage spalling of the tested material.

Concrete	w/p-ratio	w/c-ratio	Percent spalling		
			Max (%)	Min (%)	Mean (%)
40AK0	0.29	0.40	34.2	28.6	31.7
40AK2	0.28	0.40	15.0	10.9	12.5
40AK4	0.30	0.40	6.1	5.2	5.7
40AG0	0.35	0.40	22.9	15.6	18.4
40AR0	0.40	0.40	6.9	6.3	6.6
40BK0	0.31	0.40	24.7	22.5	23.8
40BR0	0.40	0.40	5.6	3.9	4.8
55BK0	0.31	0.55	27.0	26.4	26.7
55BK2	0.32	0.55	16.6	14.1	15.4
55BK4	0.34	0.55	15.6	12.8	14.2
55BR0	0.55	0.55	18.3	10.1	14.2
70BK0	0.41	0.70	21.0	16.2	18.4
70BK2	0.40	0.70	3.5	3.3	3.4
70BK4	0.39	0.70	15.4	12.7	14.1
70BG0	0.56	0.70	15.0	10.0	12.6
70BR0	0.73	0.73	8.2	7.0	7.6

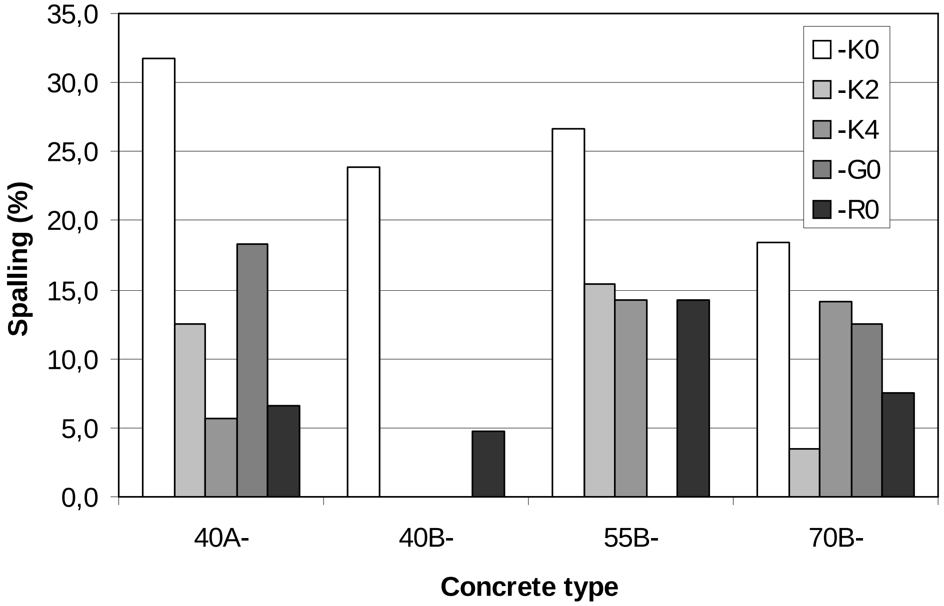

Figure 4.7 The amount of spalling for each concrete type.

The amount of fine material in the concrete affects the permeability and thus may affect the spalling. In figures 4.8-10 are the function between the water-powder ratio, i.e. the ratio between weight of water divided with weight of cement and filler, and the amount of spalling. Figure 4.8 show the relation for the concretes without fibres stored in water. These results indicates a linear relation between the amount of spalling and the water-powder ratio. A linear relation is also found for the air conditioned specimens without fibres, see figure 4.9. There is, however, one outlier and the curve is not as steep as for the specimens stored in water.

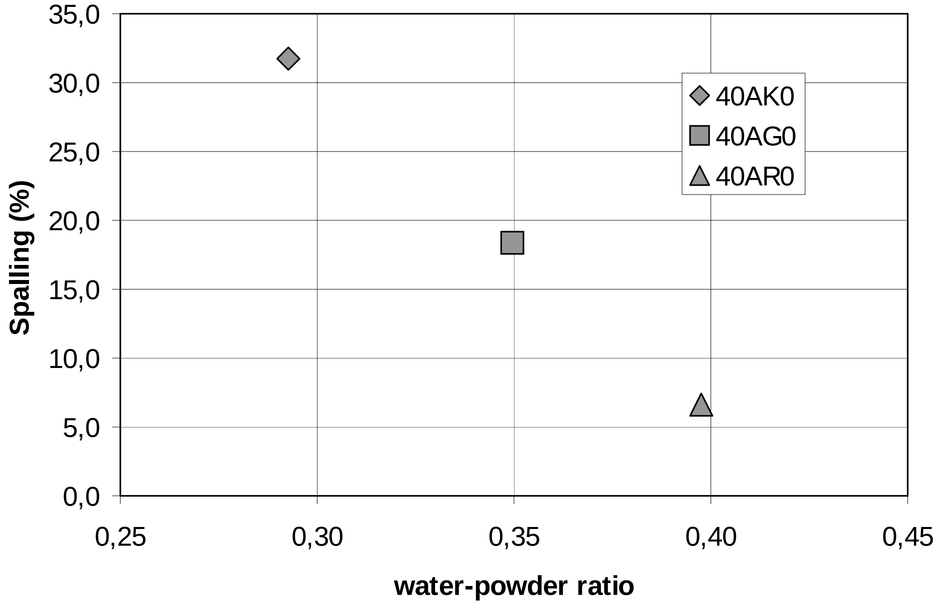

Figure 4.8 The amount of spalling as a function of the water-powder ratio (w/p) for concrete stored in water and without fibres.

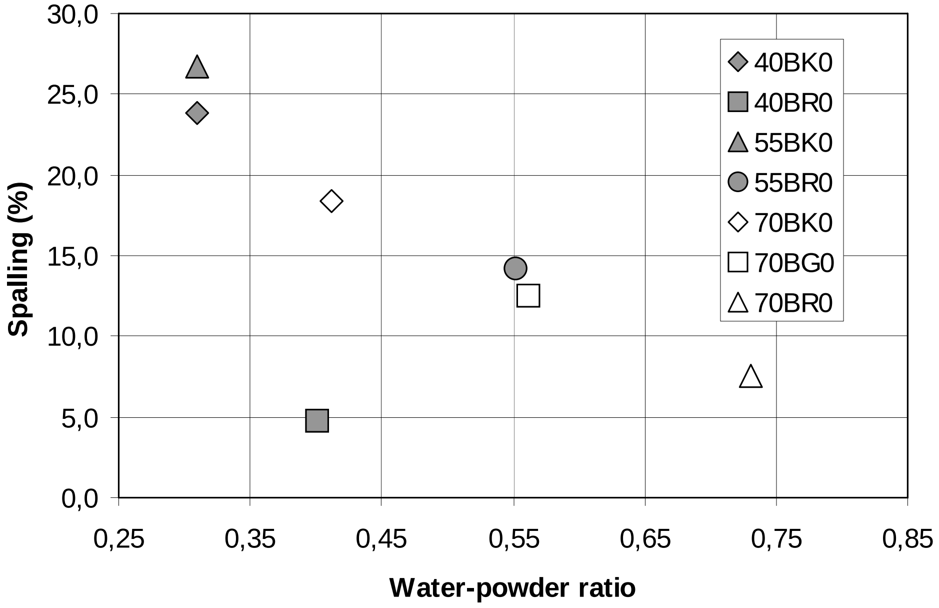

Figure 4.9 The amount of spalling as a function of the water-powder ratio (w/p) for concrete stored in air and without fibres.

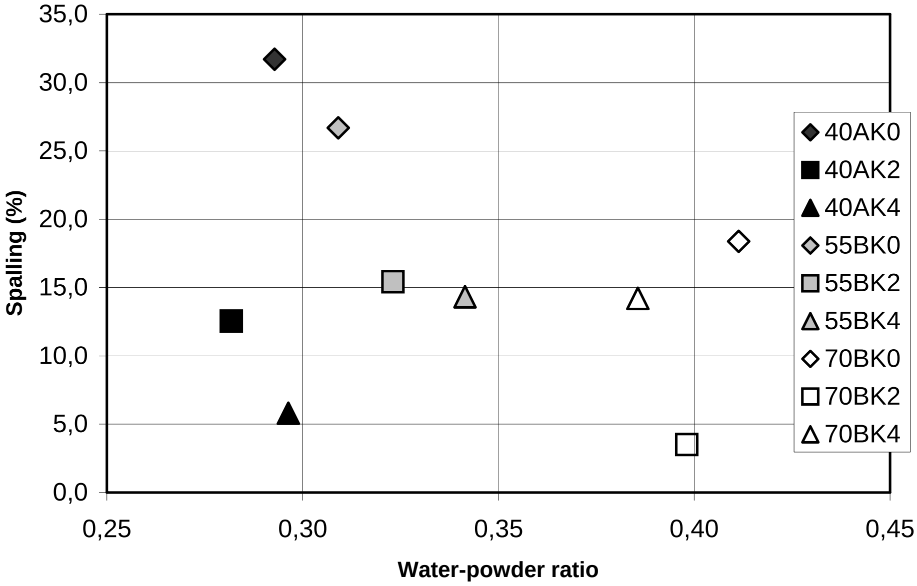

Figure 4.10 The amount of spalling as a function of the water-powder ratio (w/p) for self compacting concrete with limestone filler with different amount of fibres.

4.5 Temperature in the concrete

The temperature in the test specimens was in each specimen measured with 10 thermocouples of type K. The measurements were made at two heights of the columns and at different depths. All results from the temperature measurements are presented in Appendix A.

When designing concrete constructions for a fire scenario, it is normal to use the 500 °C isotherm, i.e. the position in the construction where the temperature equals 500 °C after a certain time. Figures 4.11 and 4.12 show the depth in the concrete as a function of time when the concrete reaches the temperature 500 °C. It should be noted that these isotherms cannot be compared with other isotherms given in the literature since there were a substantial spalling from the surface for many specimens and thus the cross sectional dimensions changed during the test.

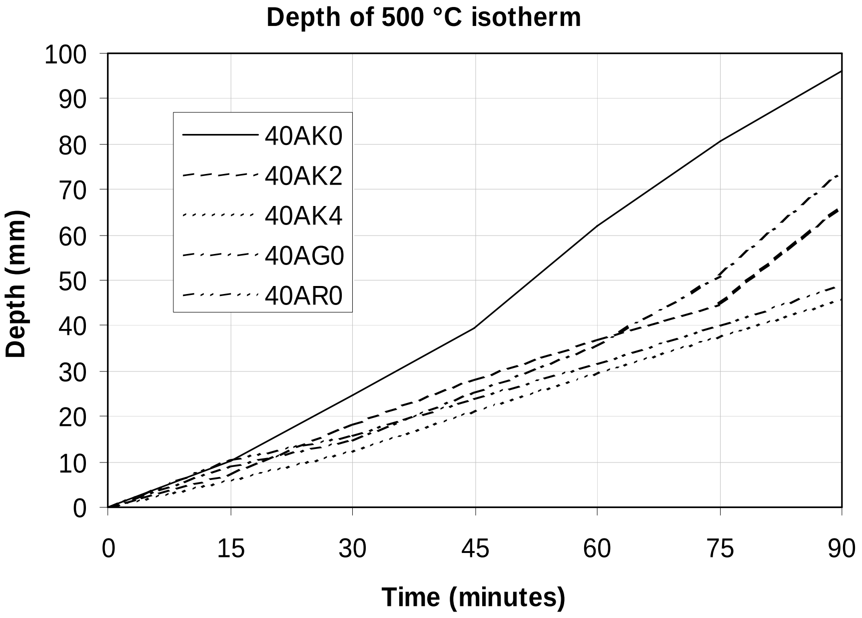

Figure 4.11 500 °C isotherm for specimens exposed to the HC-curve.

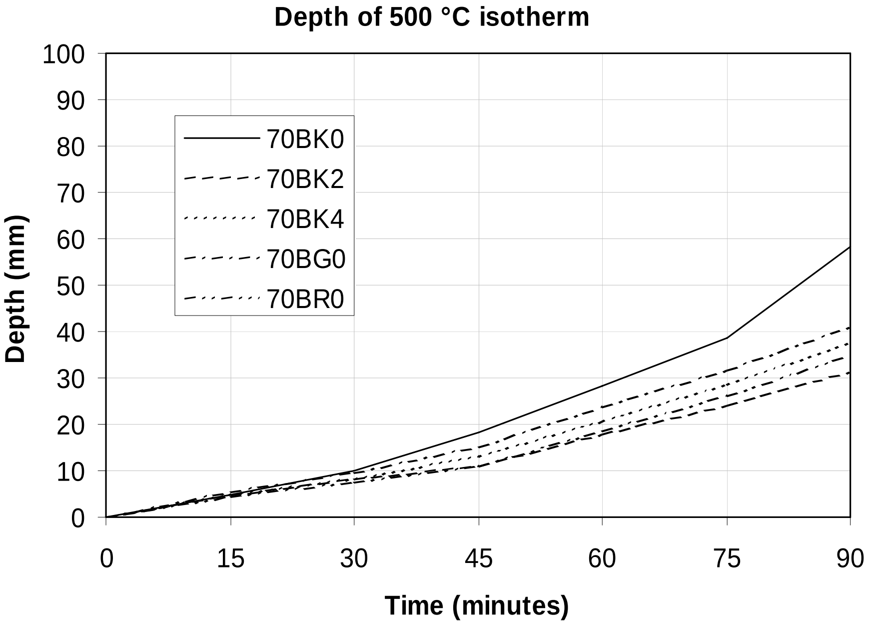

Figure 4.12 500 °C isotherm for specimens with w/c-ratio = 0.70 exposed to the standard fire curve in accordance with EN 1363-1 (ISO 834).

4.6 Observations during the tests

The spalling occurred first at the corners. The spalling started in test 1 after about 2 minutes, in test 2 after about 6 minutes and test 3 after about 7 minutes. For the self compacting concrete without polypropylene fibres the spalling was generally explosive. In all tests the spalling stopped after about 20 minutes.

It was possible to observe water coming out from the surface of the test specimens. In some cases the water was squirting from the specimens. In test 1 water could be observed after about 10 minutes, in test 2 after about 18 minutes and in test 3 after about 13 minutes.

4.7 Observations after the furnace tests

As expected were the corners of the specimens most fractured. Figures 4.13-24 show all specimens after the fire test. More photos of the individual test specimens are presented in Appendix B.

Figure 4.13 Test specimens 40AK0-1, 40AK2-1 and 40AK4-1 from left to right.

Figure 4.14 Test specimens 40AG0-1, 40AR0-1 and 40AK0-2 from left to right.

Figure 4.15 Test specimens 40AK2-2, 40AK4-2 and 40AG0-2 from left to right.

Figure 4.16 Test specimens 40AR0-2, 40AK0-3, 40AK2-3 and 40AG0-3 from left to right.

Figure 4.17 Test specimens 40BK0-1, 40BR0-1 and 55BK0-1 from left to right.

Figure 4.18 Test specimens 55BK2-1, 55BK4-1 and 55BR0-1 from left to right.

Figure 4.19 Test specimens 55BK0-2, 40BR0-2 and 40BK0-2 from left to right.

Figure 4.20 Test specimens 55BK2-2, 55BK4-2, 55BR0-2 and 40BK0-3 from left to right.

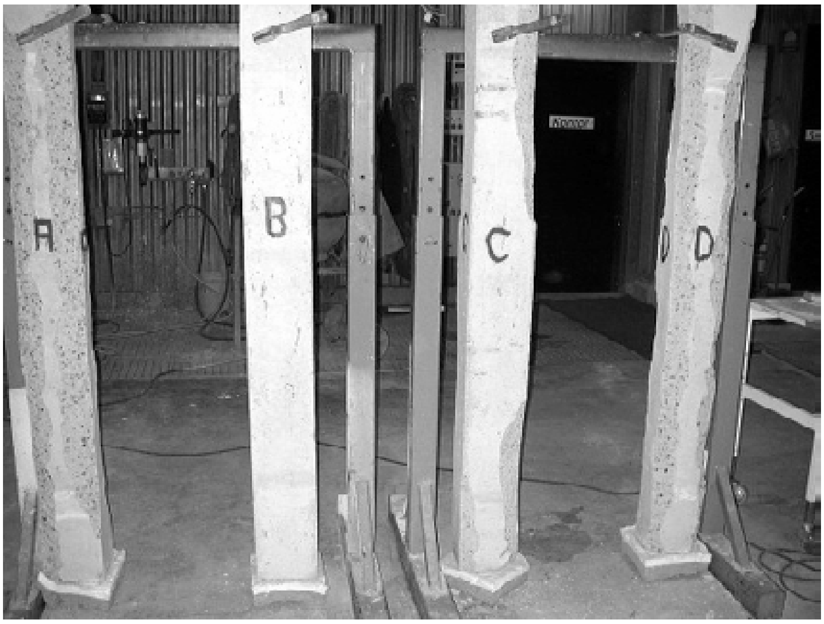

Figure 4.21 Test specimens 70BK0-1, 70BK2-1, 70BK4-1 and 70BG0-1 from left to right.

Figure 4.22 Test specimens 70BR0-1, 70BK0-2 and 70BK2-2 from left to right.

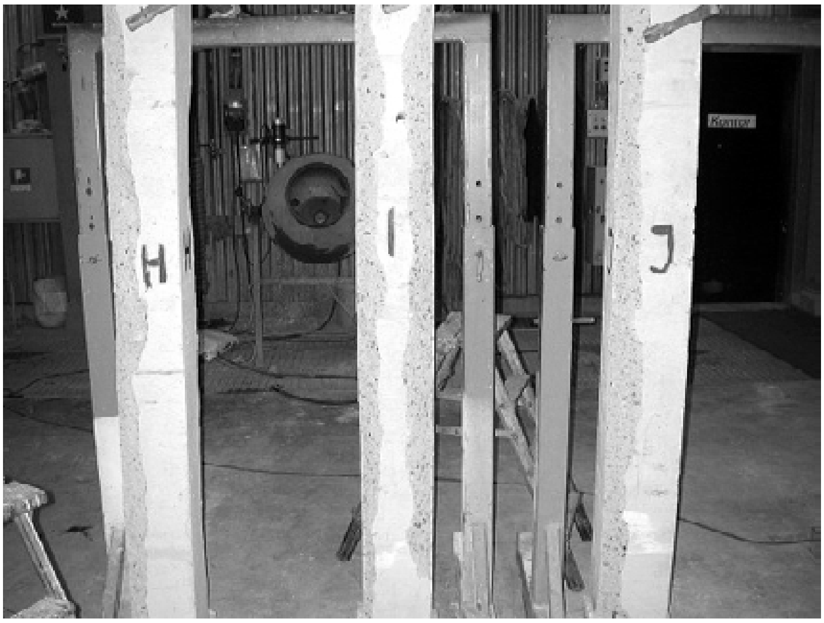

Figure 4.23 Test specimens 70BK4-2, 70BG0-2 and 70BR0-2 from left to right.

Figure 4.24 Test specimens 70BK0-3, 70BK2-3, 70BK4-3 and 70BG0-3 from left to right.

5 Discussion

A relevant question is whether any spalling can be accepted and if so to what extent. In the present tests, all test specimens spalled to some extent. Some more and some less. If no spalling is acceptable it would be difficult to draw any conclusions from the presented tests, and it would in most cases be difficult to use concrete when fire resistance is required. Therefore some extent of spalling must be allowed. Within the scope of this report no recommendations on acceptable levels of spalling has been made due to the limited number of tests and test configurations.

There are several factors that affects the amount of spalling such as concrete recipe, moisture content, specimen geometry and load application. It shall be noted that even if there in some cases were extensive spalling in the present study, there may well be applications in practise where the concrete works well. Some factors point in a positive direction while others in a negative direction. The concrete was relative young when tested, only six months. It is well known that the strength increases with age. If the concrete is older than six months one can expect a better behaviour, i.e. less spalling. The moisture content was relatively high, and if the moisture content is lower the amount of spalling will decrease. The square geometry of the test specimens, and the four sided fire exposure gives very severe conditions with respect to spalling. For other geometries and fire loads the spalling may well be less. On the other hand was the load applied as pre-stressed reinforcement bars, and an external load may give an increased spalling.

Self compacting concrete is not one product but a family of products with the only similarity that it is self compacting and composed of cement, aggregates, water and additives. There are many different varieties of self compacting concrete and these tests have only examined a few. Even if these tests in some cases showed an extensive spalling it may well be possible by using other mixtures self compacting concrete can be made with a good fire resistance.

With the concretes included in this study a linear relation was obtained between the amount of spalling and the water-powder ratio. Note that these relations was only found for concretes without fibres. Furthermore, different kind of fillers were used and thus it is not clear if these relations also depends on type of filler or not.

6 Conclusions and recommendations

A total of twelve different self compacting concretes as well as four conventional concretes have been fire tested. The following results were obtained:

- All test specimens spalled to some extent. The amount of spalling varied between 3 % and 34 %.
- Most spalling was observed for self compacting concrete with limestone filler stored in water.
- Adding polypropylene fibres decreased the amount of spalling to the same level as for conventional concrete with the same water-cement ratio.
- These tests gave a linear relation between the amount of spalling and the water-powder ratio for the concretes without polypropylene fibres.

These tests showed that severe spalling may occur for self compacting concrete exposed to fire. They also showed that it may be possible to decrease the amount of spalling by including polypropylene fibres in the mixture. Although, there are still several questions which must be answered before any recommendations can be made on how to produce fire resistant self compacting concrete. There is thus a need for more research. The following would need further investigations:

- effect of filler
- effect of age of the concrete
- effect of fibre amount
- effect of fibre type and geometry
- effect of specimen geometry
- effect of moisture content
- effect of loading conditions and load level
- effect of fire load

Several of the above mentioned effects have been studied for other types of concrete as conventional and high performance concrete, and thus a control must be made to see if self compacting concrete behaves similarly.

References

[1] Blontrock H., Taerwe L. (2002): “Exploratory spalling tests on self compacting concrete”, Proc. 6th International Symposium on Utilization of High Performance Concrete, Germany

[2] Nevander L.E., Elmarsson B. (1994): ”Fukthandbok” (eng. Moisture handbook), AB Svensk Byggtjänst, Sweden

[3] Persson B. (2003) Report to be published

[4] CERIB (2001) “Caractérisation du comportement au feu des Bétons Auto-Plaçants“, Report DT/DCO/2001/21, France

Appendix

Appendices are presented in the included CD. The following show the contents of the appendices.

Appendix A - Temperatures in concrete at full scale tests

- Concrete 40AK0
- Concrete 40AK2
- Concrete 40AK4
- Concrete 40AG0
- Concrete 40AR0
- Concrete 40BK0
- Concrete 40BR0
- Concrete 55BK0
- Concrete 55BK2
- Concrete 55BK4
- Concrete 55BR0
- Concrete 70BK0
- Concrete 70BK2
- Concrete 70BK4
- Concrete 70BG0
- Concrete 70BR0

Appendix B - Photos of test specimens

- Test specimens before furnace test
- Test specimens during furnace test
- Test series 1 - HC-curve
  - General view after test
  - Concrete 40AK0
  - Concrete 40AK2
  - Concrete 40AK4
  - Concrete 40AG0
  - Concrete 40AR0
- Test series 2 - Standard fire
  - General view after test
  - Concrete 40BK0
  - Concrete 40BR0
  - Concrete 55BK0
  - Concrete 55BK2
  - Concrete 55BK4
  - Concrete 55BR0
- Test series 3 - Standard fire
  - General view after test
  - Concrete 70BK0
  - Concrete 70BK2
  - Concrete 70BK4
  - Concrete 70BG0
  - Concrete 70BR0

Appendix C - Mix proportions of the concrete

- Concrete with Degerhamn Standard cement
- Concrete with Skövde Bygg cement

Lars Boström

The performance of some self compacting concretes when exposed to fire

- Appendix A -
Temperatures in concrete at full scale tests

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Concrete 55BK2 24
Concrete 55BK4 25
Concrete 55BR0 26
Concrete 70BK0 27
Concrete 70BK2 31
Concrete 70BK4 35
Concrete 70BG0 39
Concrete 70BR0 43

Appendix A - Temperatures in concrete at full scale tests

Concrete 40AK0

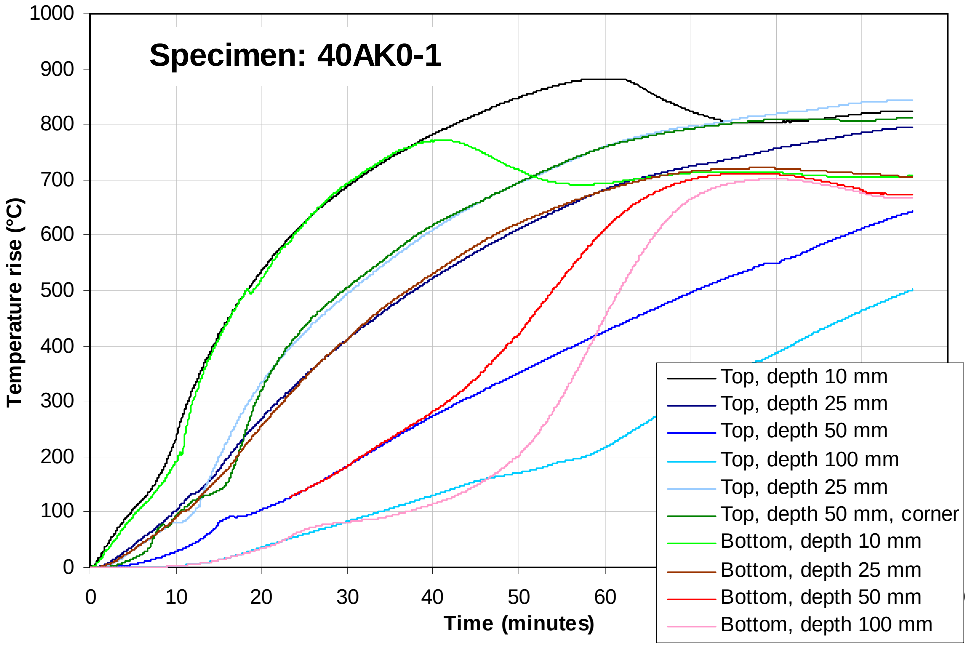

Figure A.1 Temperatures in specimen 40AK0-1.

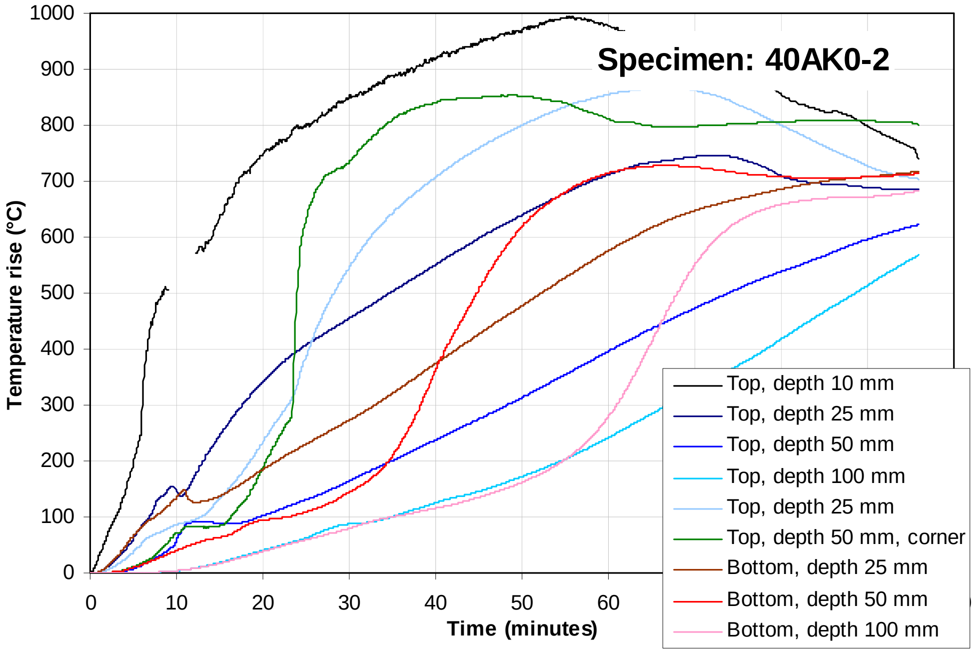

Figure A.2 Temperatures in specimen 40AK0-2.

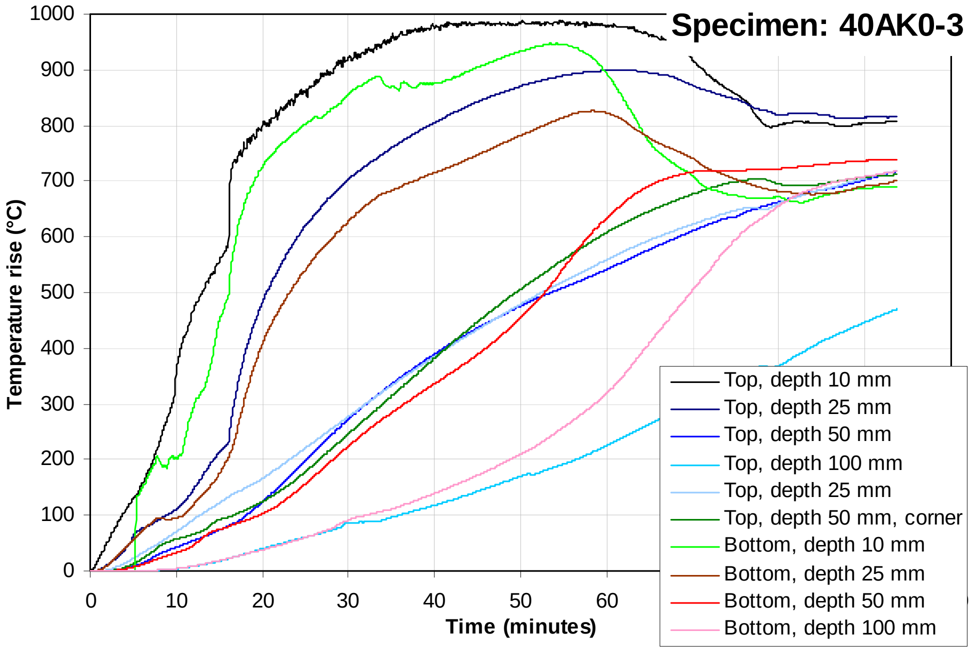

Figure A.3 Temperatures in specimen 40AK0-3.

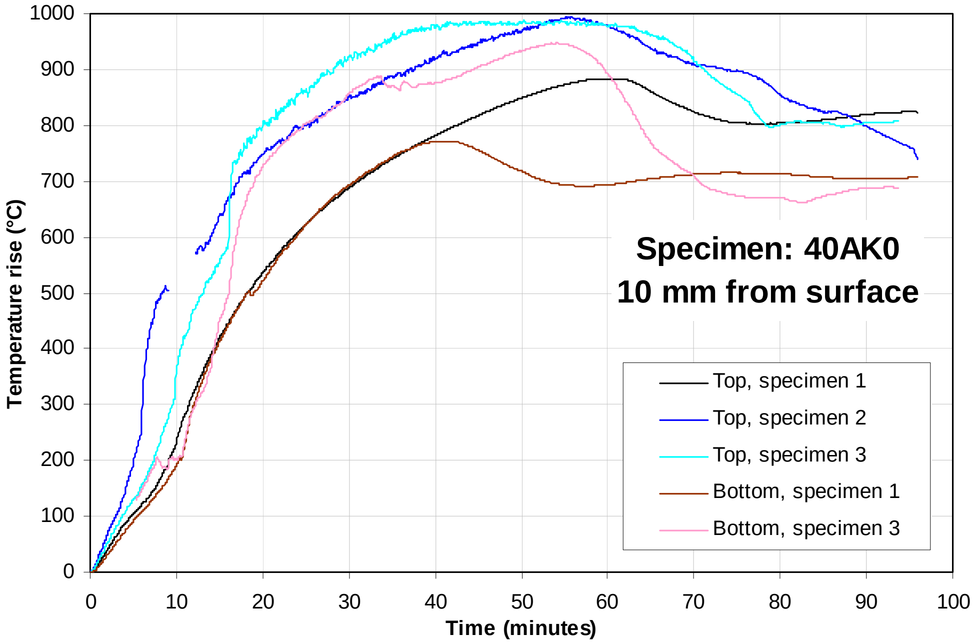

Figure A.4 Temperatures in specimen 40AK0 at 10 mm depth.

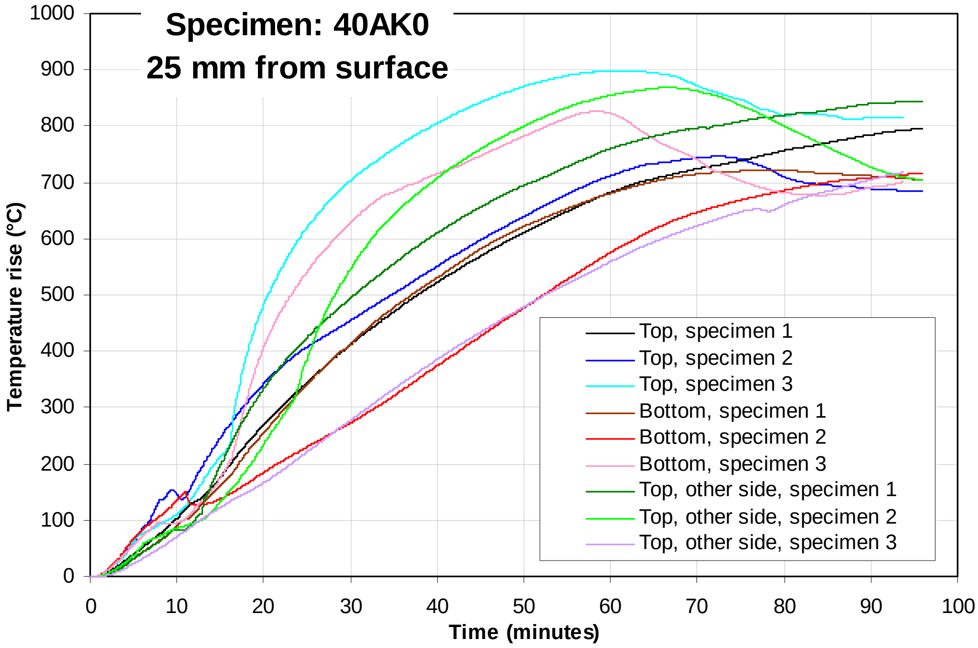

Figure A.5 Temperatures in specimen 40AK0 at 25 mm depth.

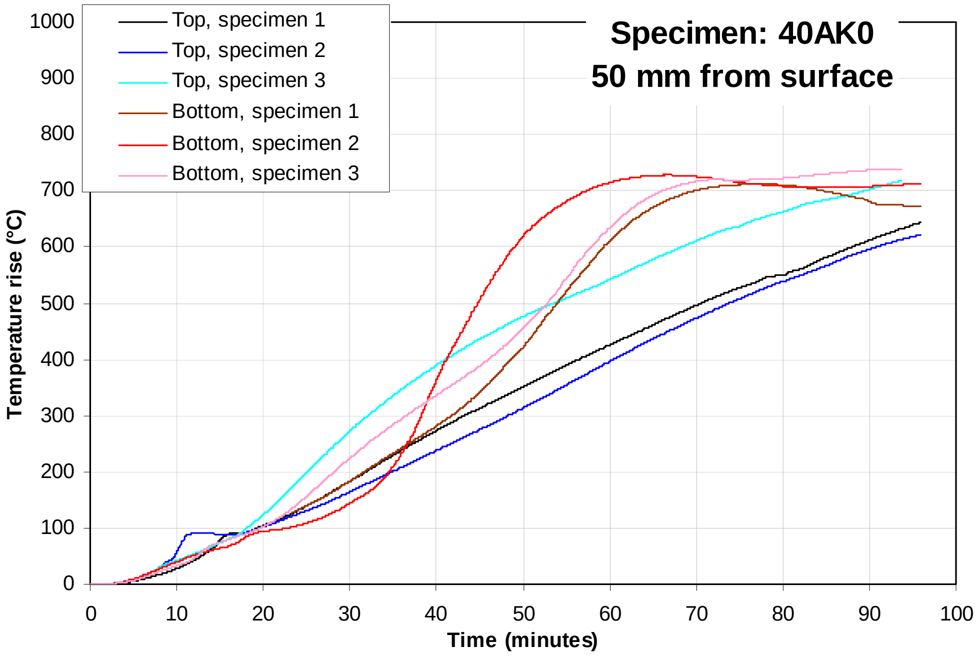

Figure A.6 Temperatures in specimen 40AK0 at 50 mm depth.

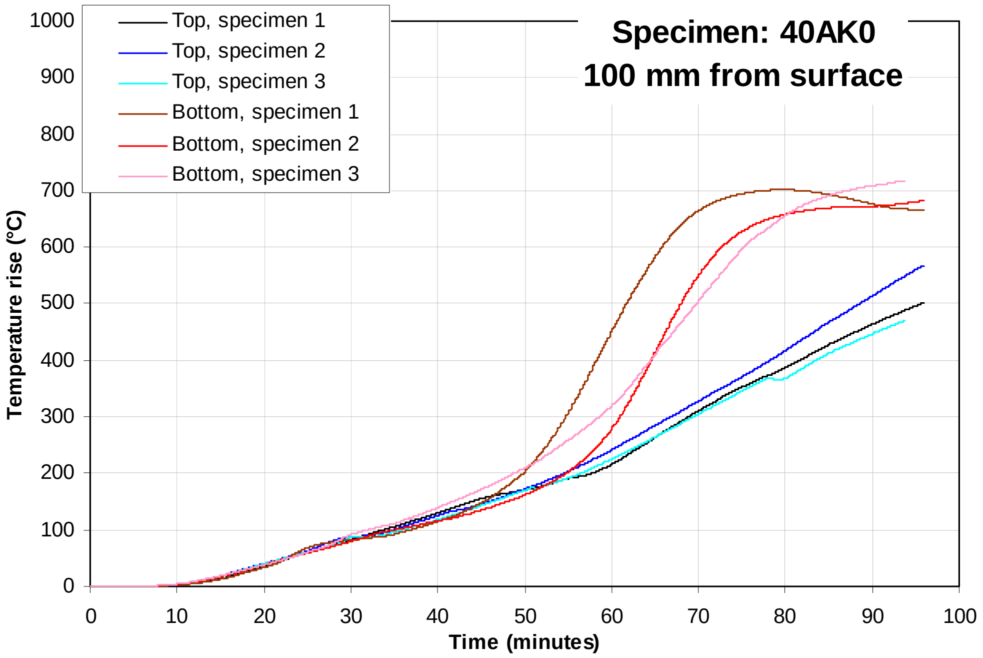

Figure A.7 Temperatures in specimen 40AK0 at 100 mm depth.

Concrete 40AK2

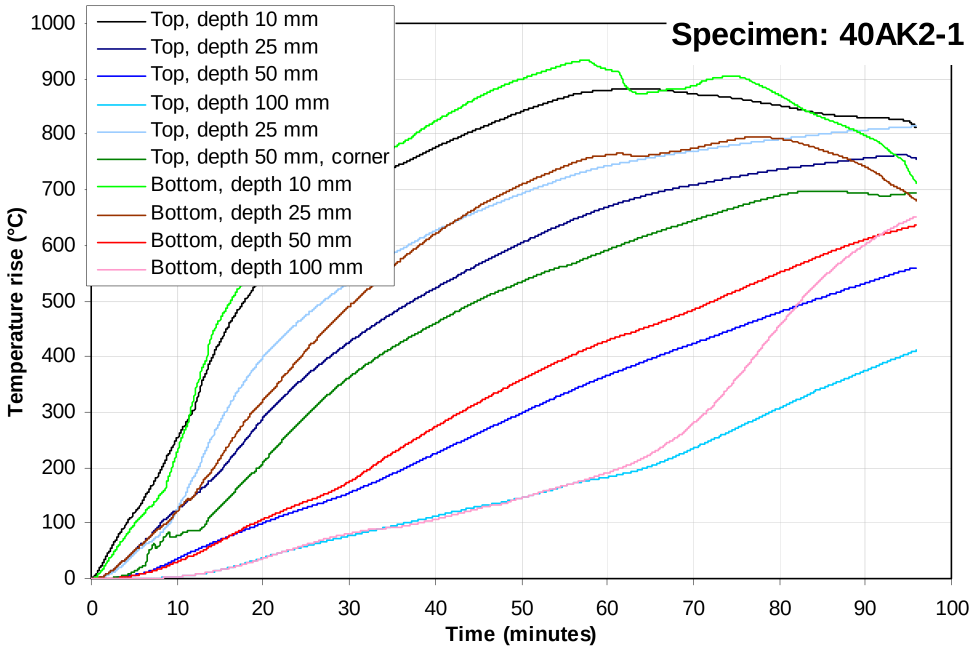

Figure A.8 Temperatures in specimen 40AK2-1.

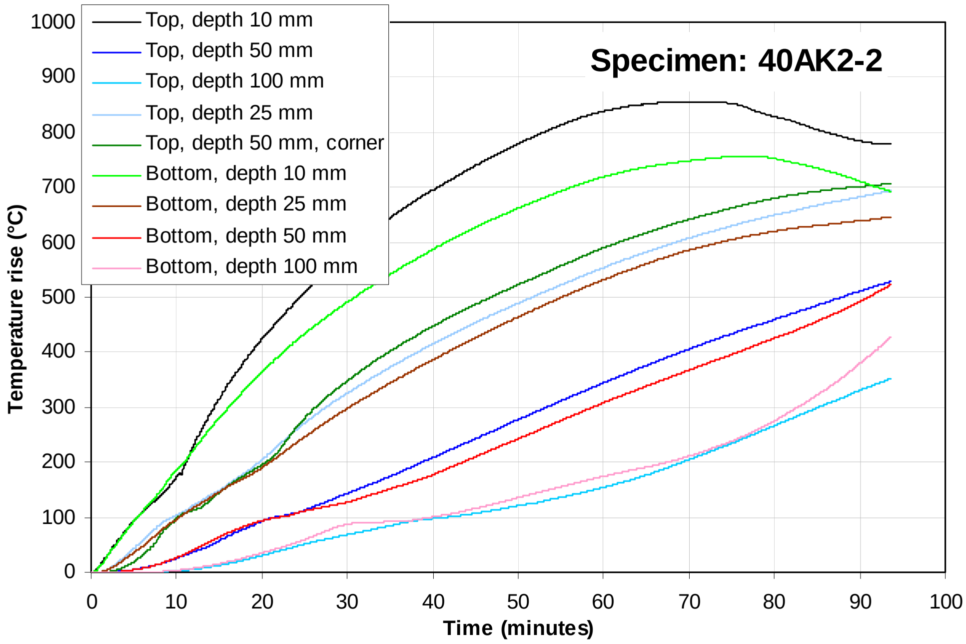

Figure A.9 Temperatures in specimen 40AK2-2.

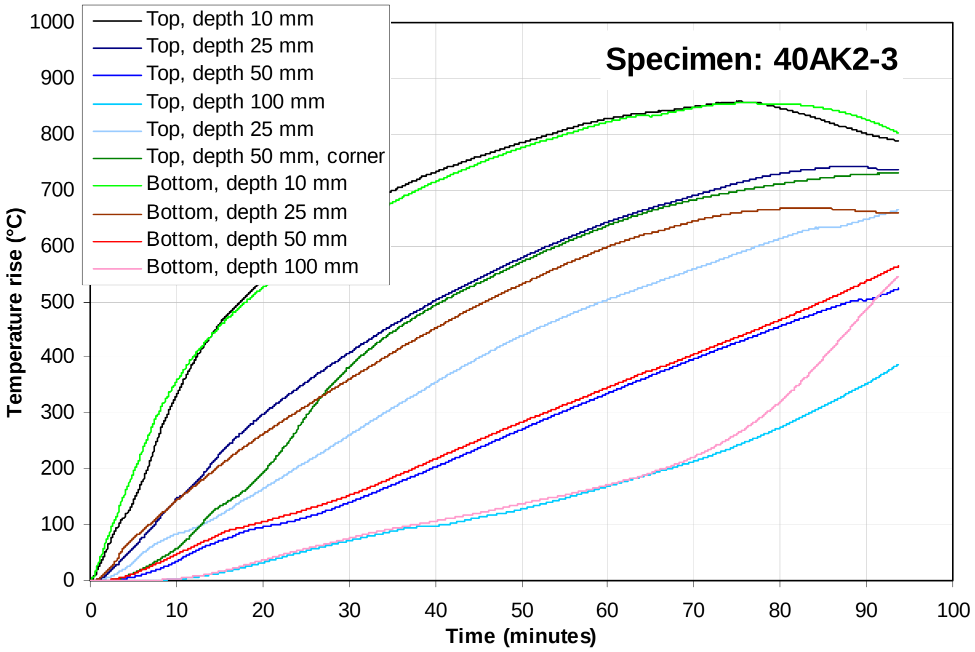

Figure A.10 Temperatures in specimen 40AK2-3.

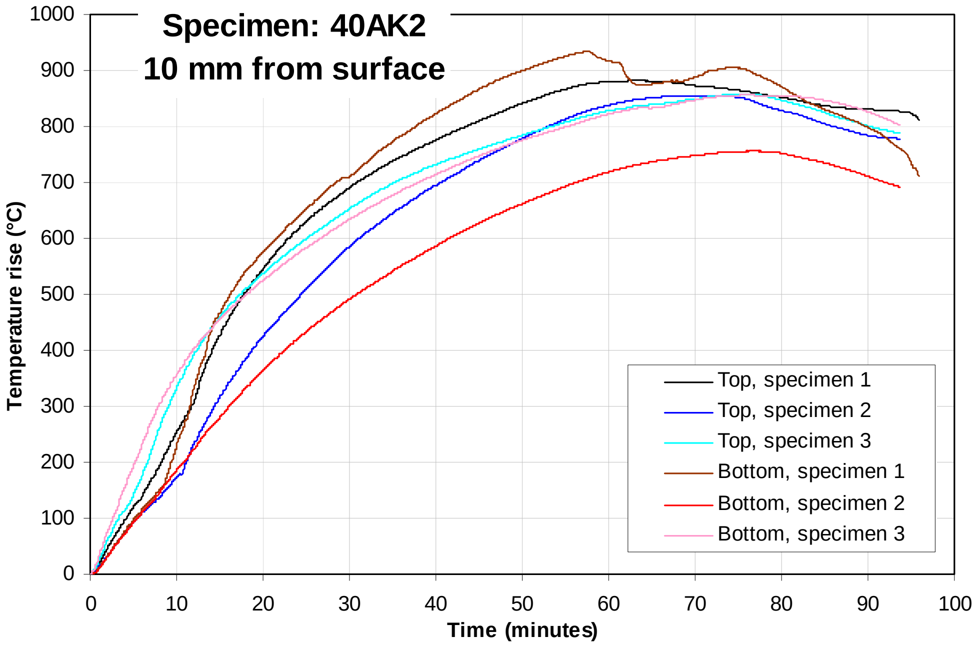

Figure A.11 Temperatures in specimen 40AK2 at 10 mm depth.

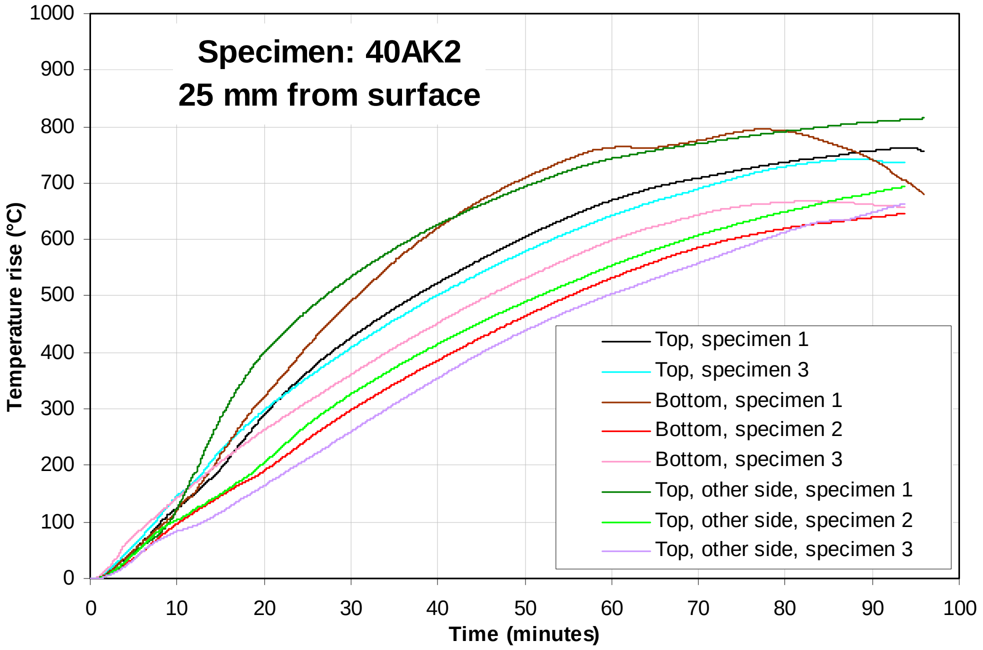

Figure A.12 Temperatures in specimen 40AK2 at 25 mm depth.

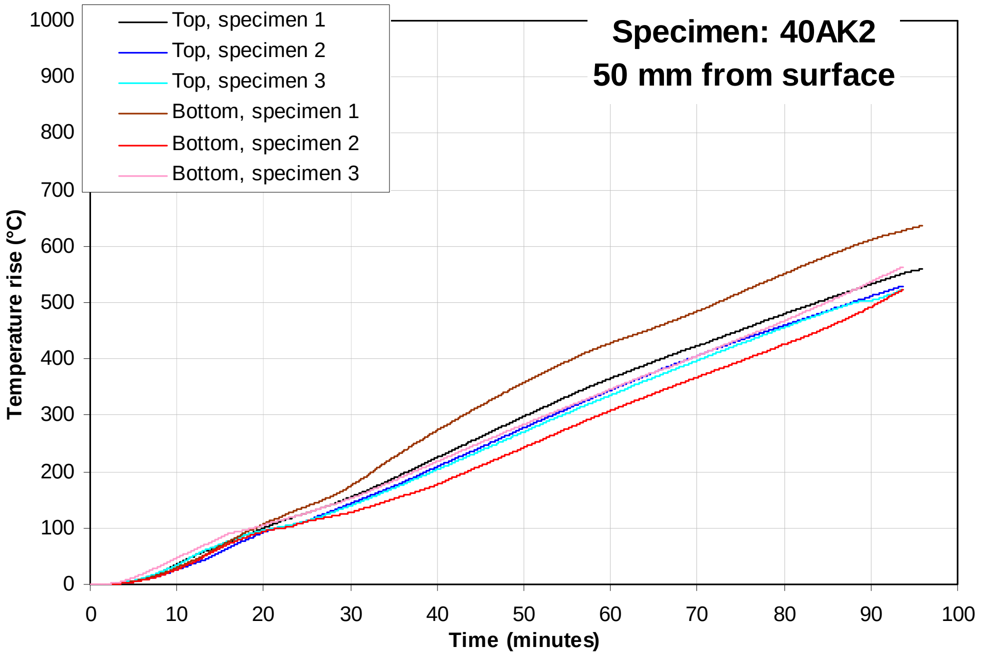

Figure A.13 Temperatures in specimen 40AK2 at 50 mm depth.

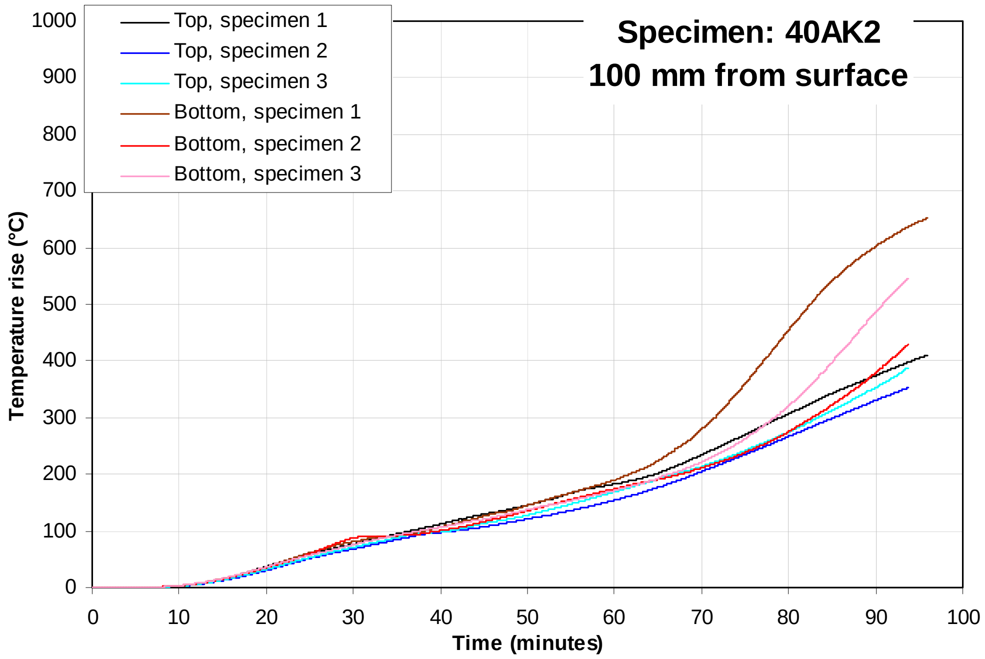

Figure A.14 Temperatures in specimen 40AK2 at 100 mm depth.

Concrete 40AK4

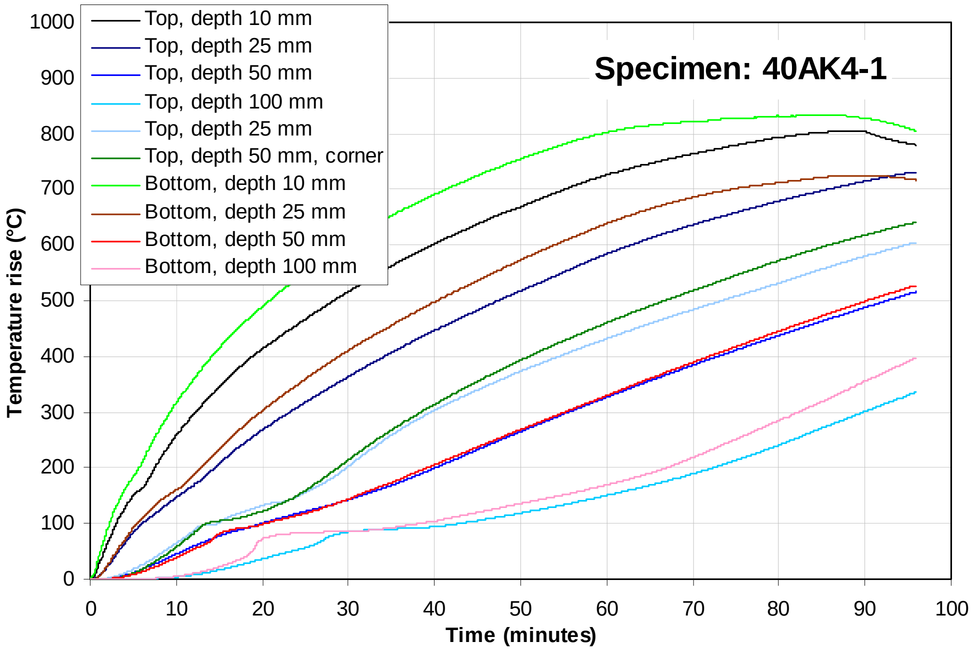

Figure A.15 Temperatures in specimen 40AK4-1.

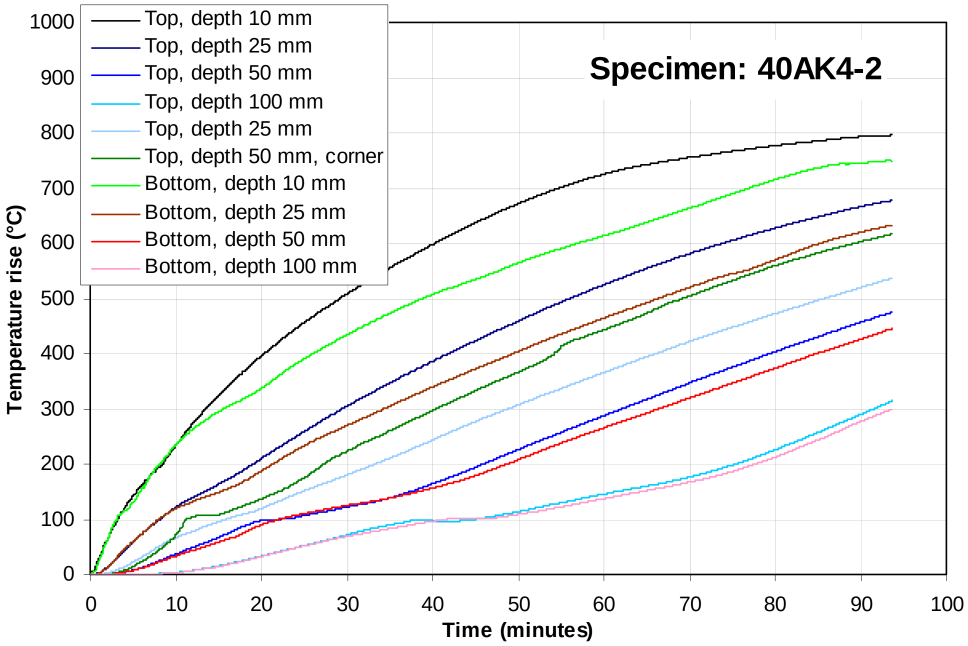

Figure A.16 Temperatures in specimen 40AK4-2.

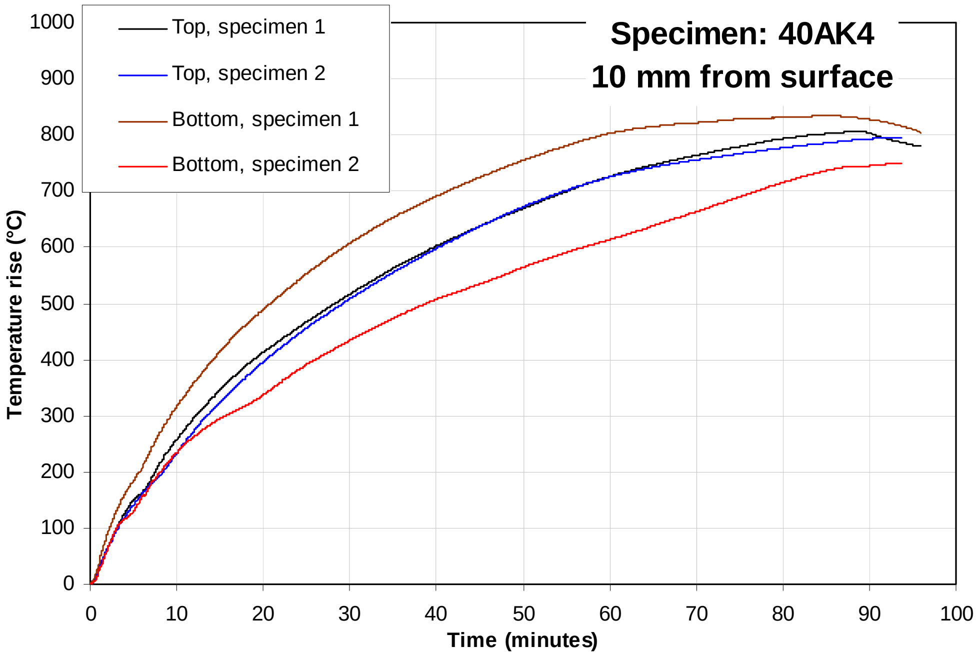

Figure A.17 Temperatures in specimen 40AK4 at 10 mm depth.

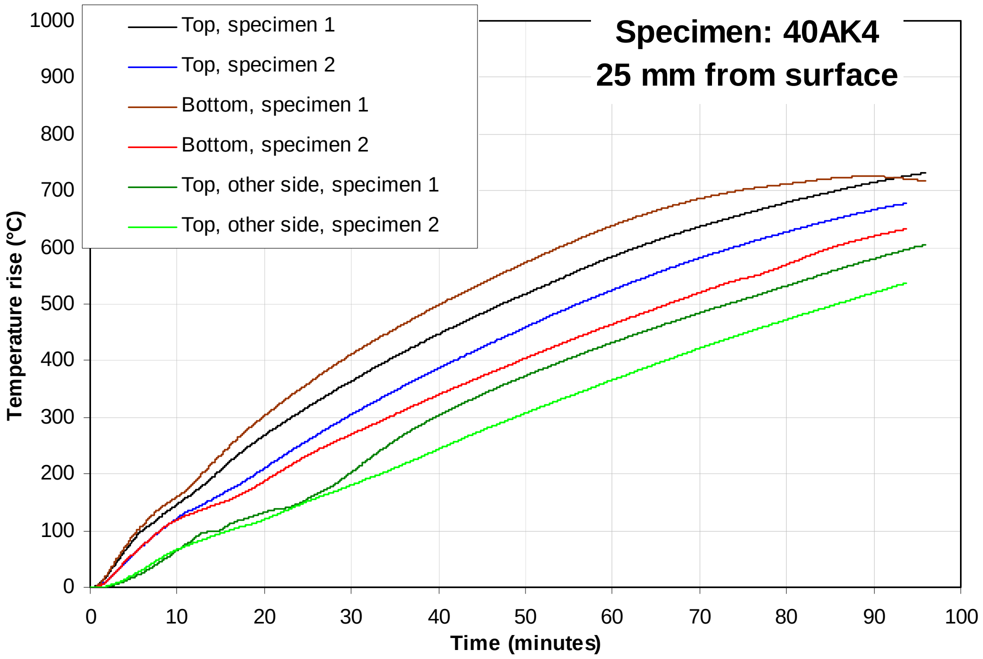

Figure A.18 Temperatures in specimen 40AK4 at 25 mm depth.

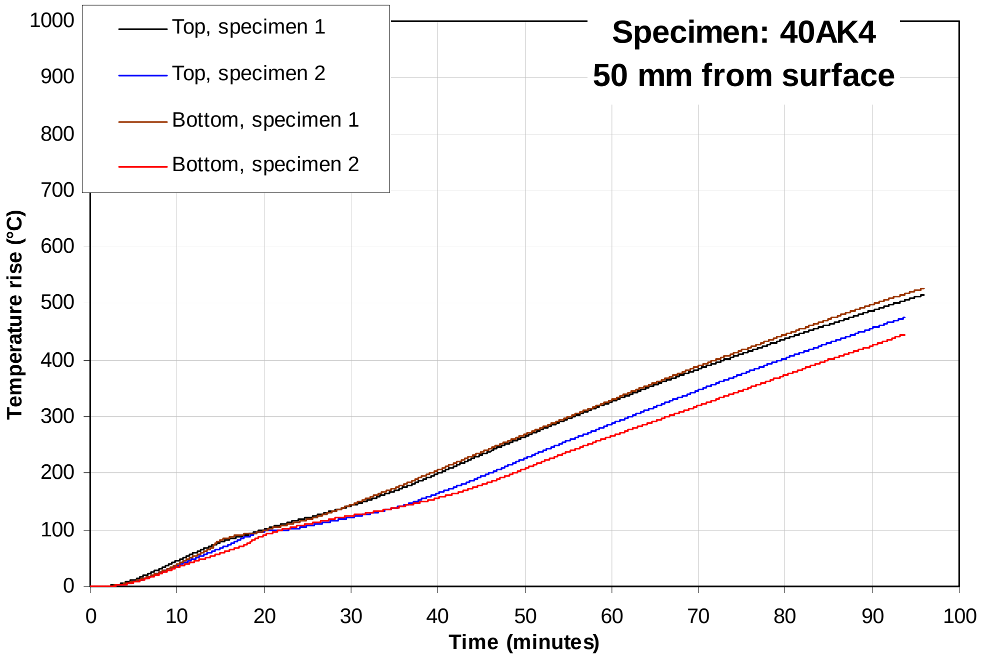

Figure A.19 Temperatures in specimen 40AK4 at 50 mm depth.

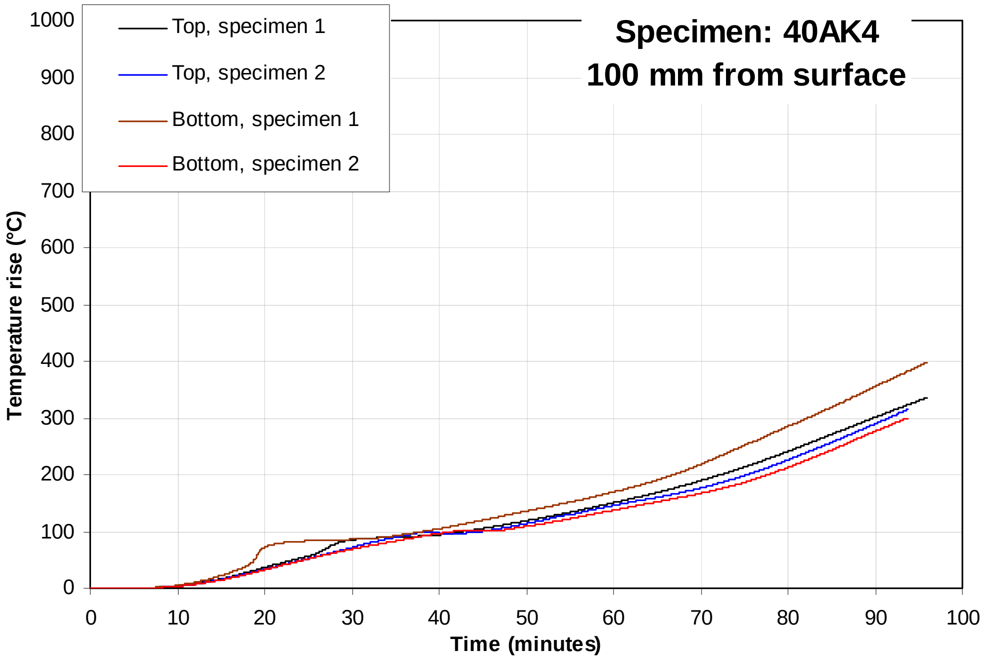

Figure A.20 Temperatures in specimen 40AK4 at 100 mm depth.

Concrete 40AG0

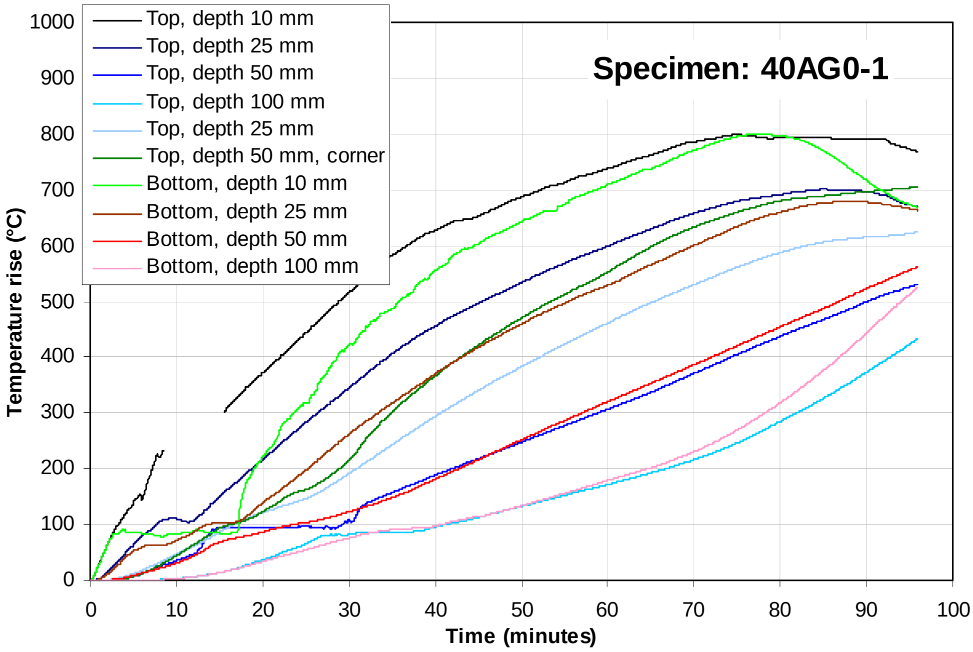

Figure A.21 Temperatures in specimen 40AG0-1.

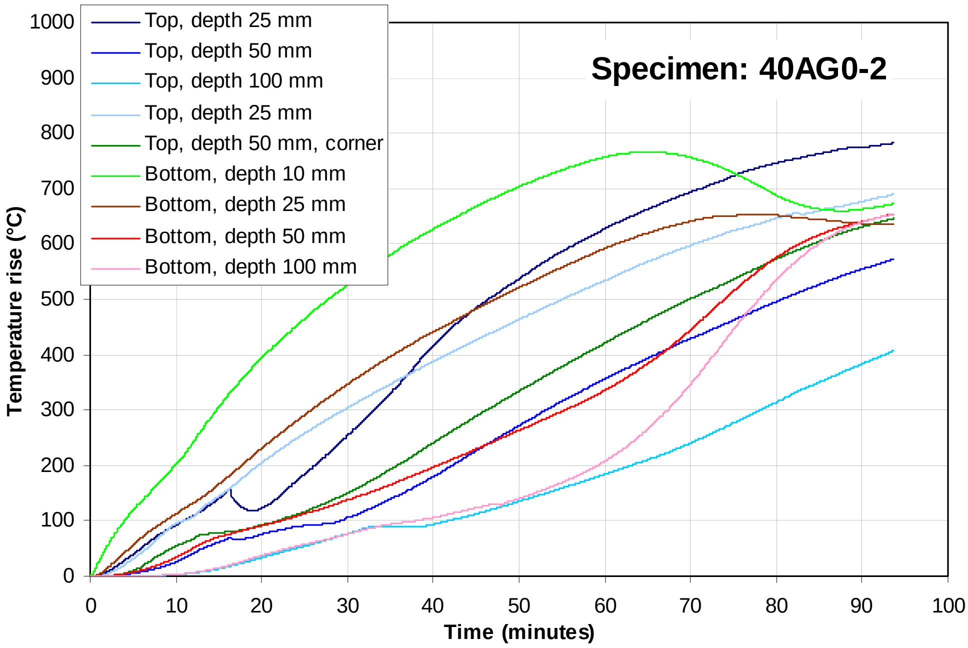

Figure A.22 Temperatures in specimen 40AG0-2.

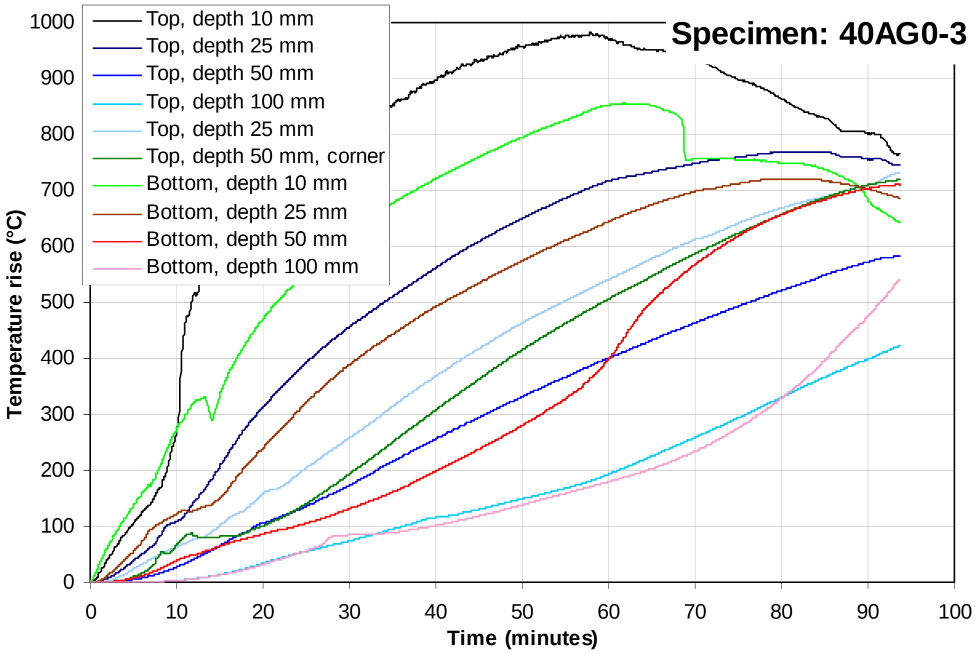

Figure A.23 Temperatures in specimen 40AG0-3.

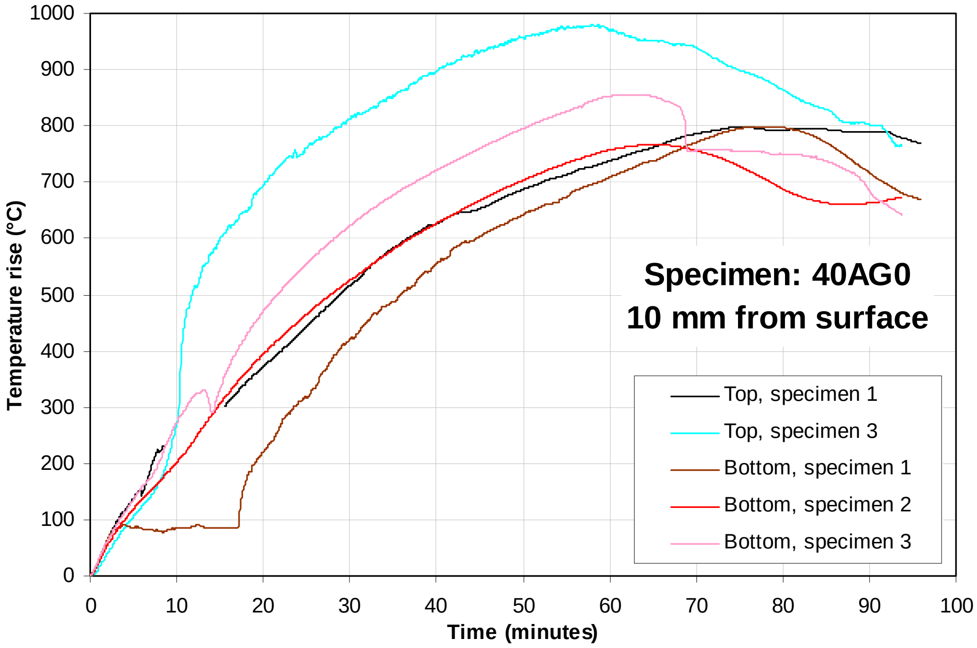

Figure A.24 Temperatures in specimen 40AG0 at 10 mm depth.

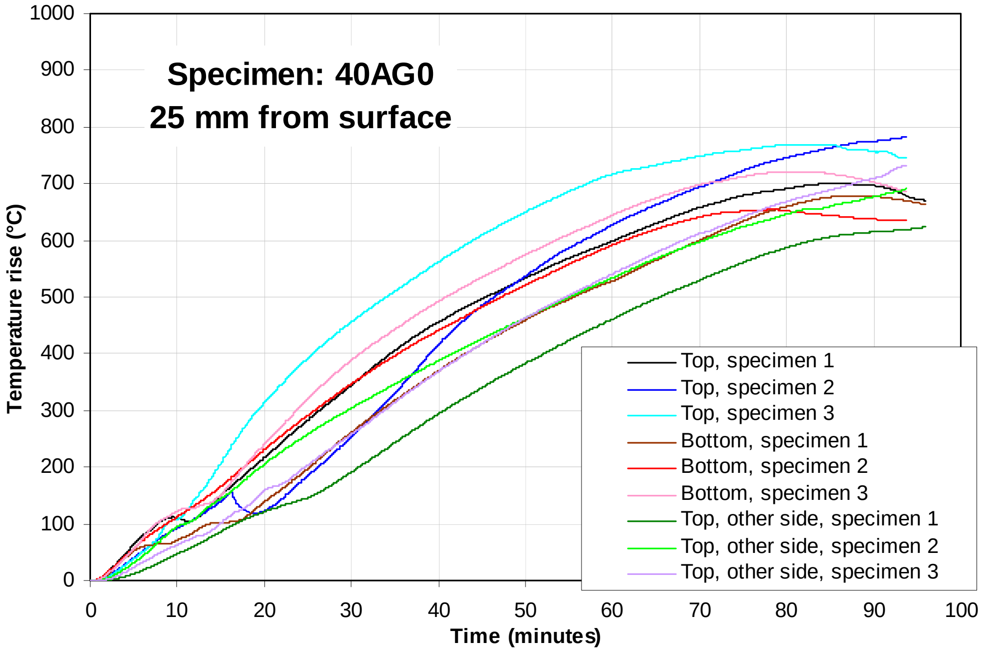

Figure A.25 Temperatures in specimen 40AG0 at 25 mm depth.

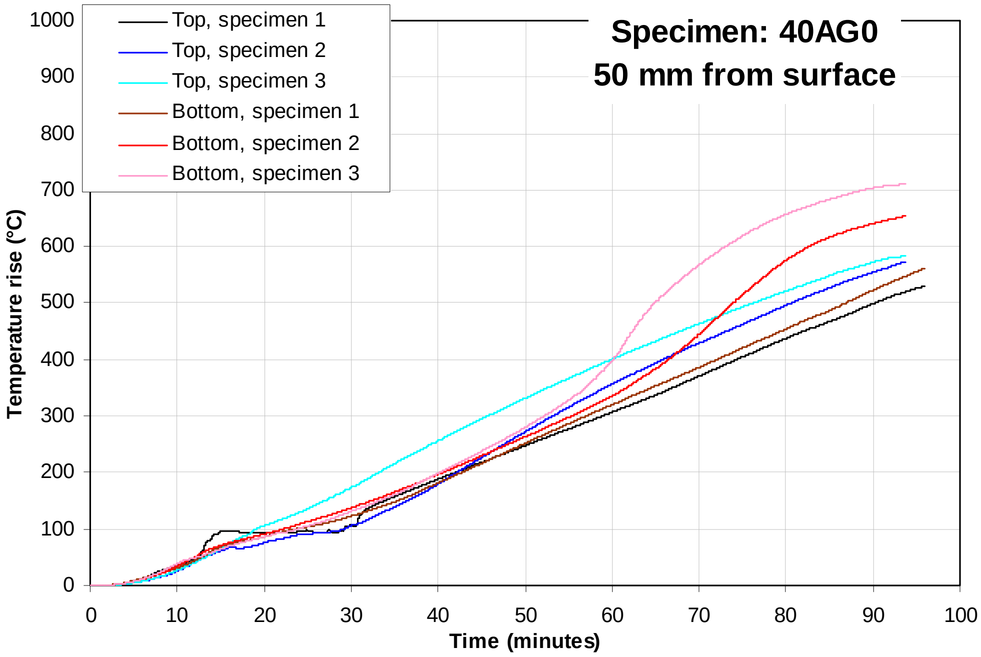

Figure A.26 Temperatures in specimen 40AG0 at 50 mm depth.

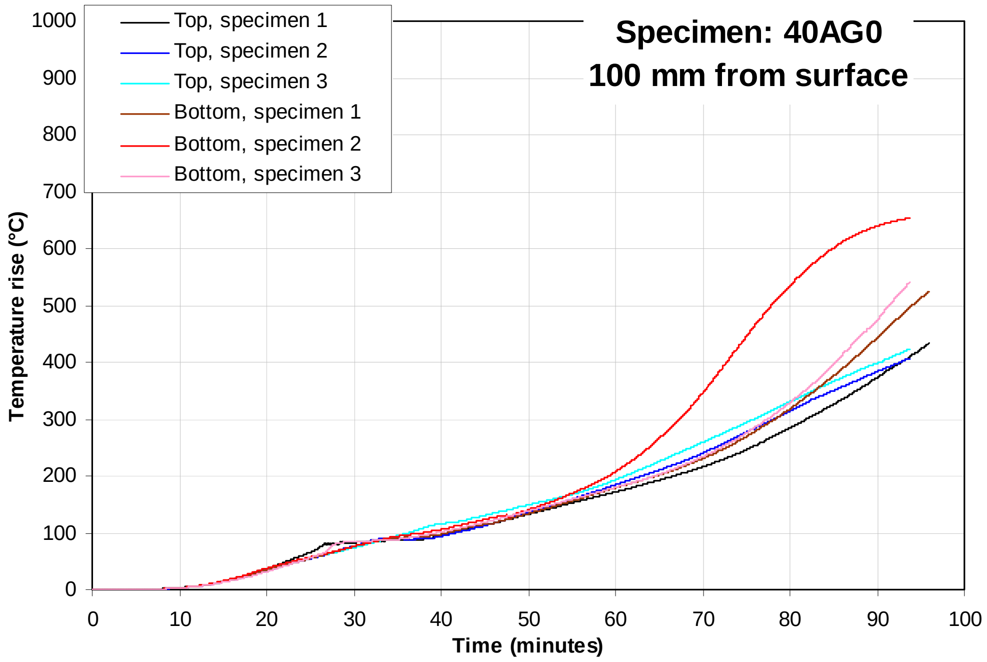

Figure A.27 Temperatures in specimen 40AG0 at 100 mm depth.

Concrete 40AR0

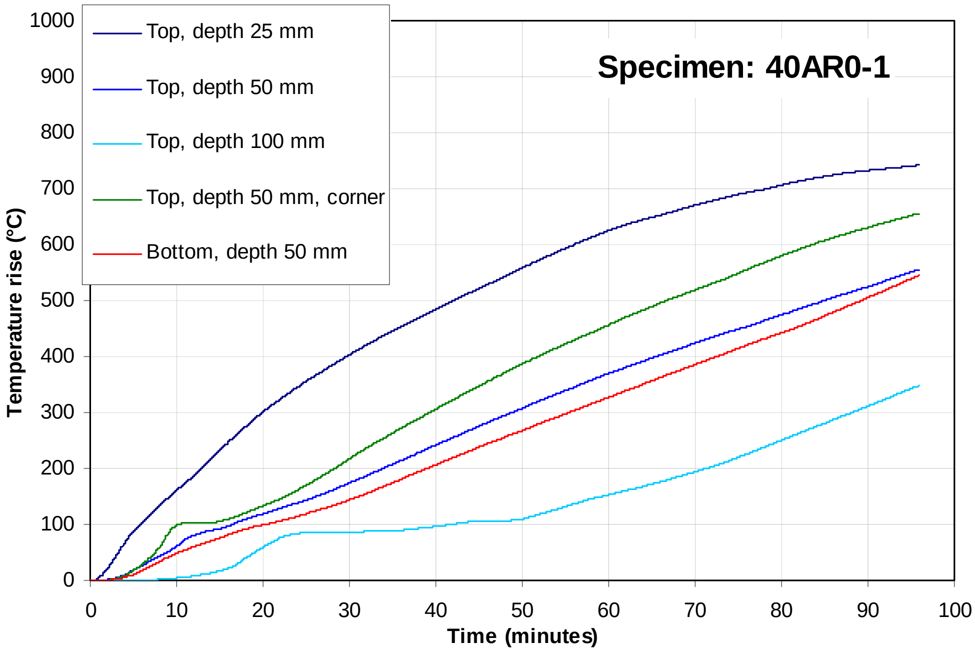

Figure A.28 Temperatures in specimen 40AR0-1.

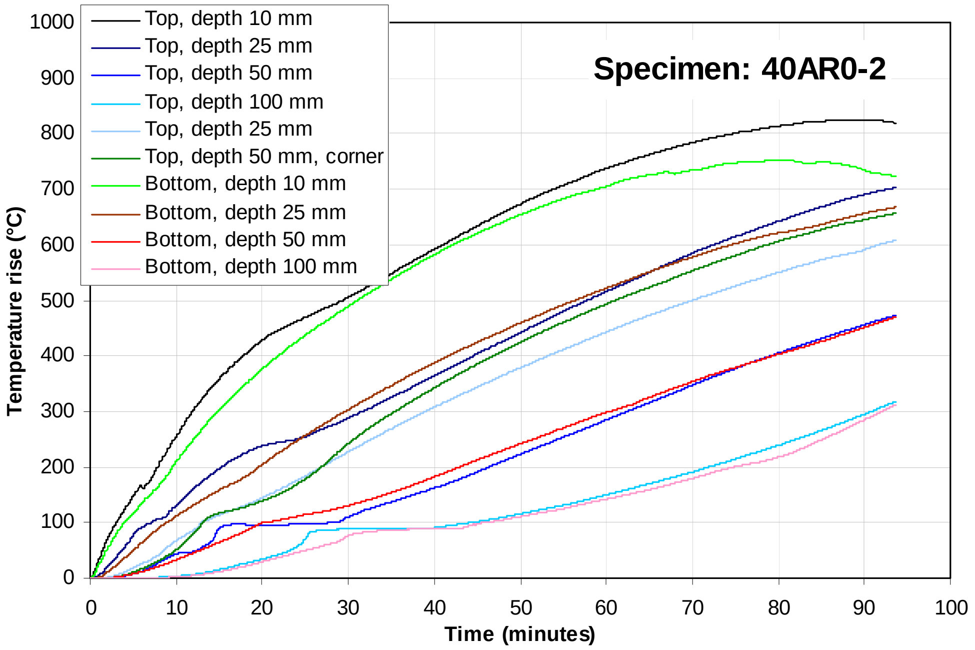

Figure A.29 Temperatures in specimen 40AR0-2.

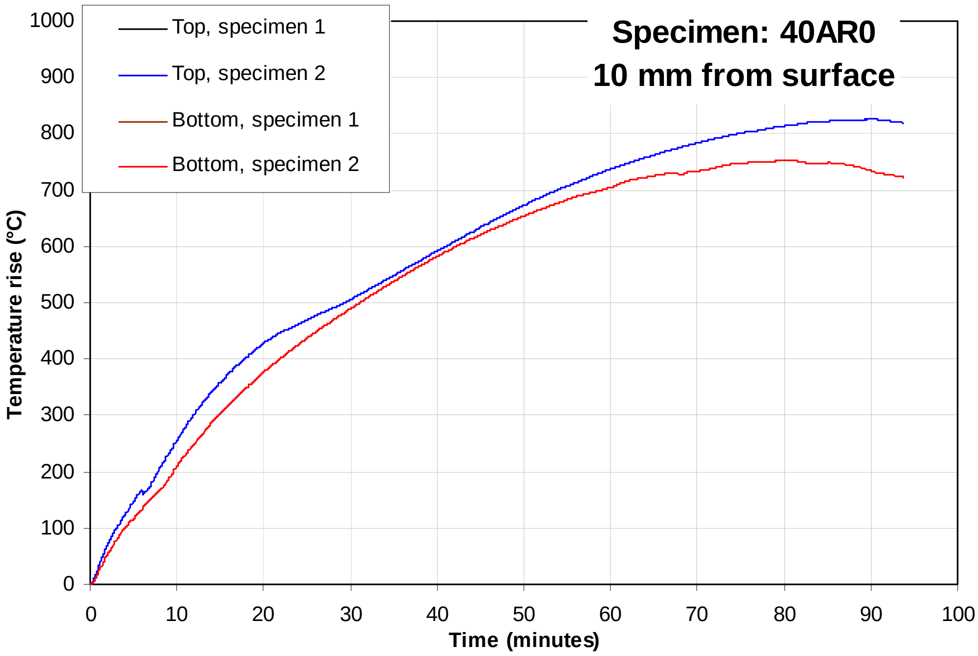

Figure A.30 Temperatures in specimen 40AR0 at 10 mm depth.

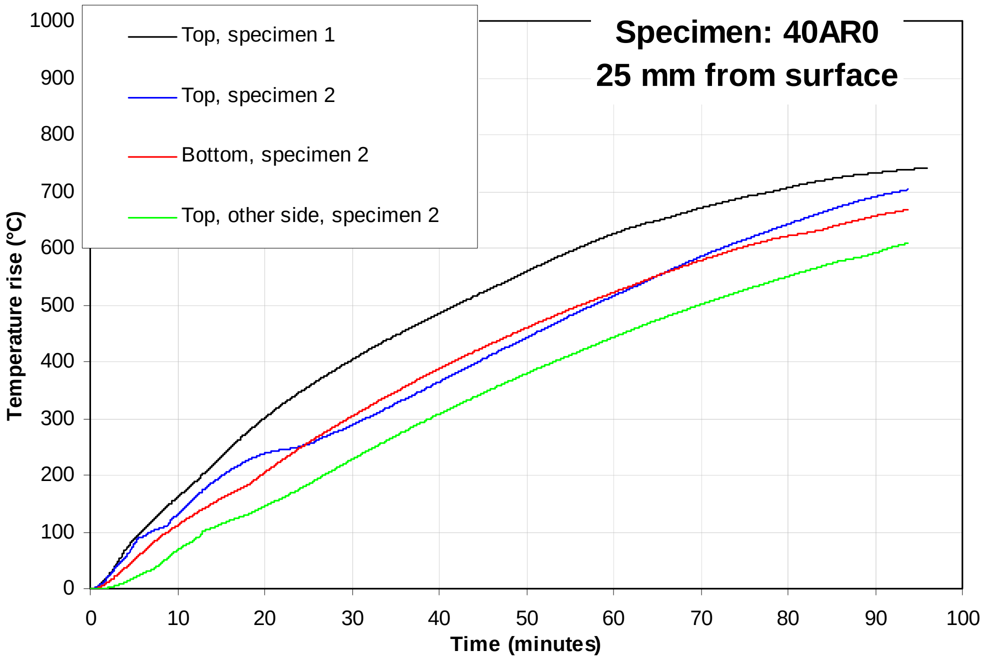

Figure A.31 Temperatures in specimen 40AR0 at 25 mm depth.

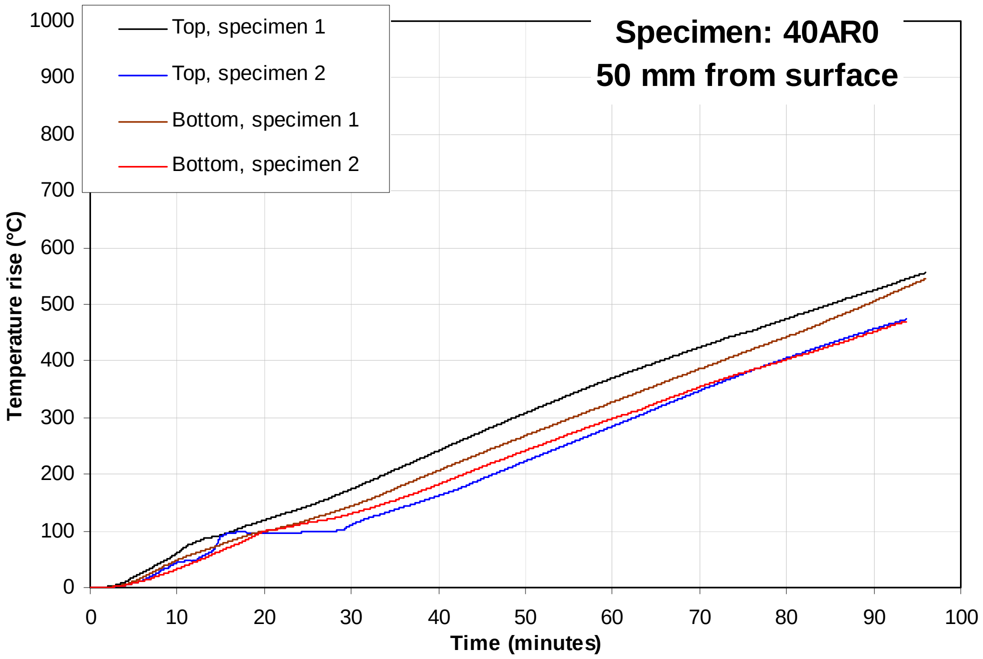

Figure A.32 Temperatures in specimen 40AR0 at 50 mm depth.

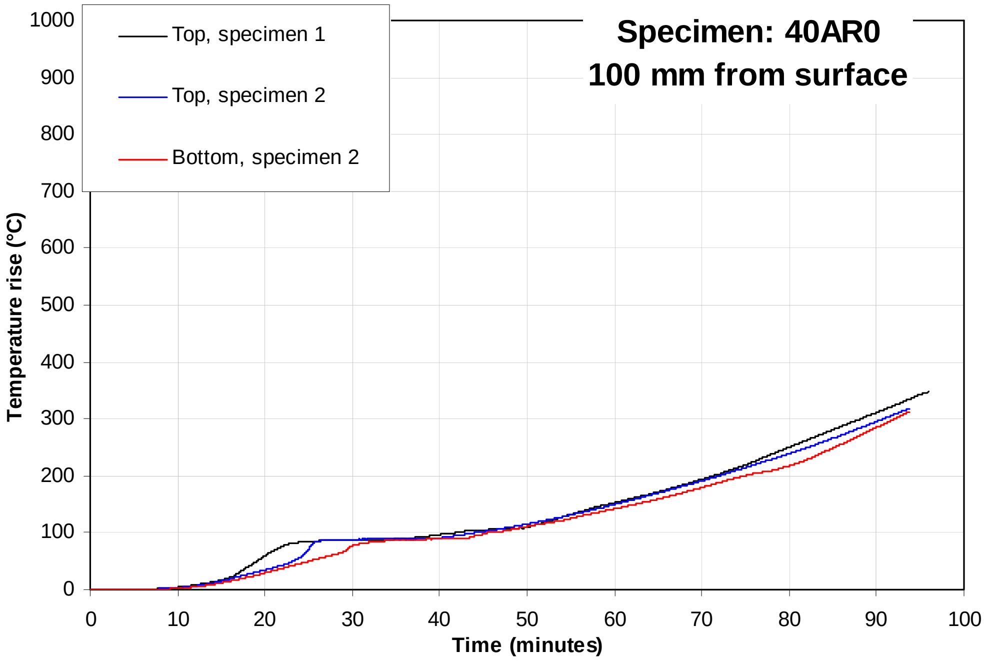

Figure A.33 Temperatures in specimen 40AR0 at 100 mm depth.

Concrete 40BK0

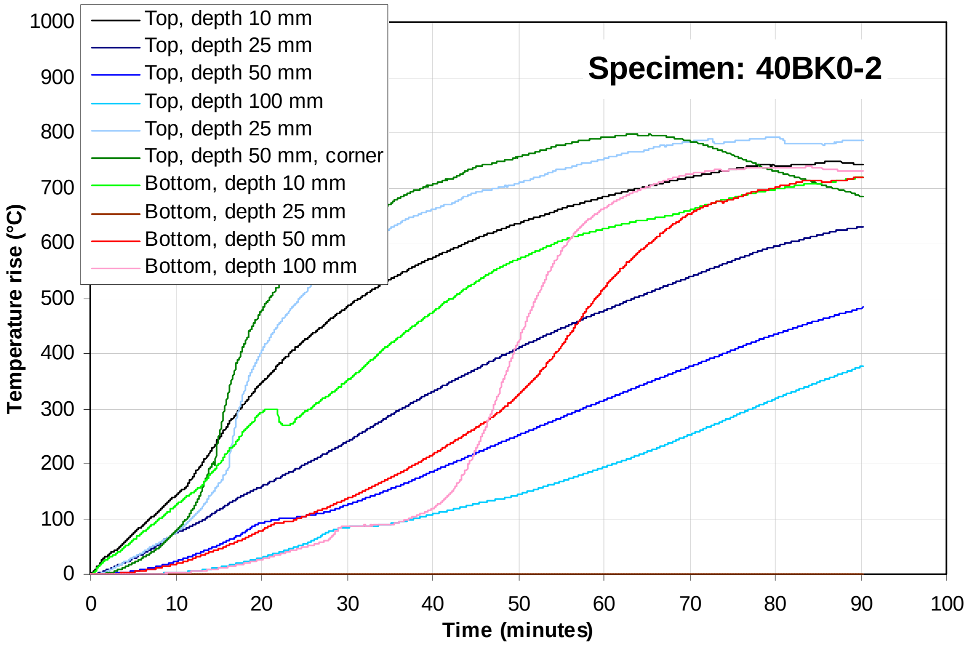

Figure A.34 Temperatures in specimen 40BK0-2.

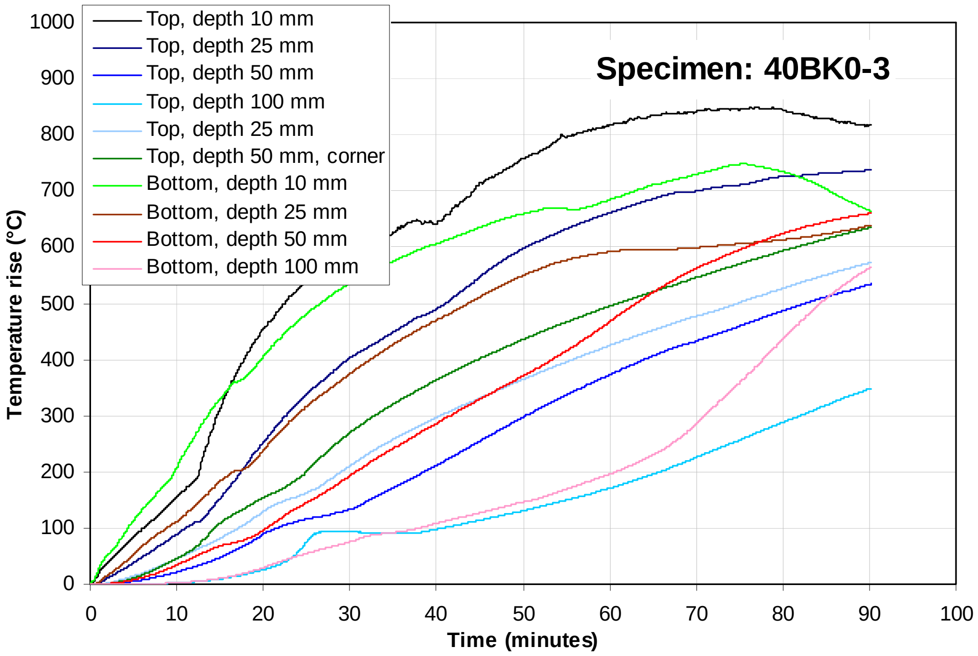

Figure A.35 Temperatures in specimen 40BK0-3.

Concrete 40BR0

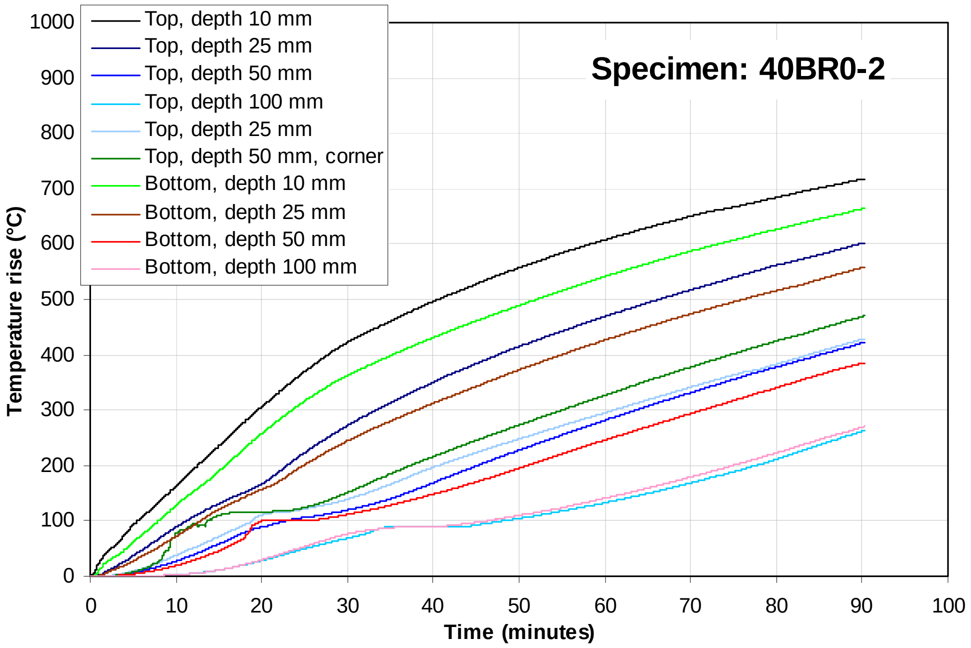

Figure A.36 Temperatures in specimen 40BR0-2.

Concrete 55BK0

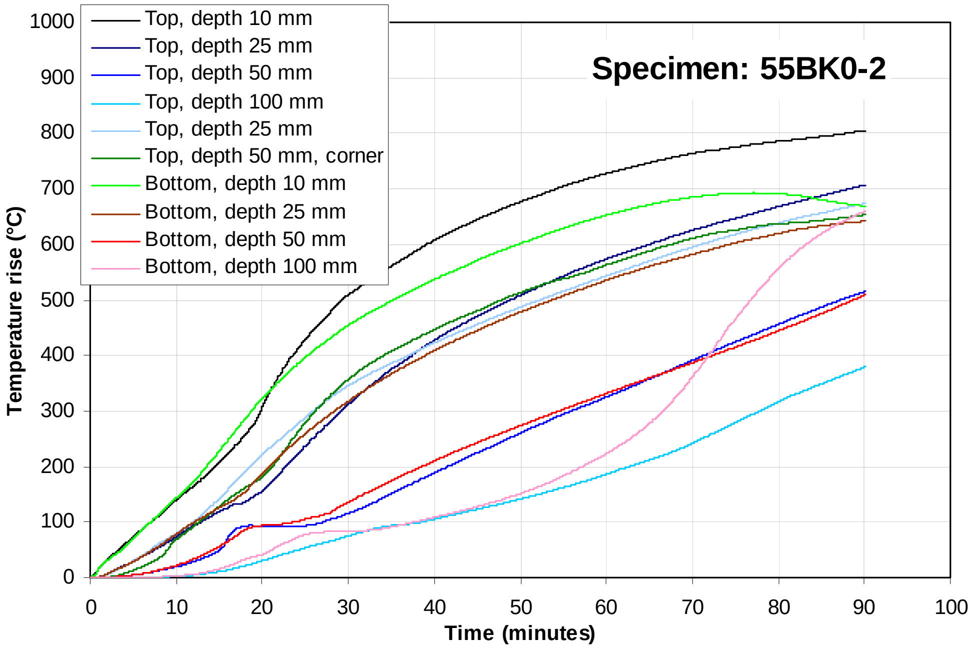

Figure A.37 Temperatures in specimen 55BK0-2.

Concrete 55BK2

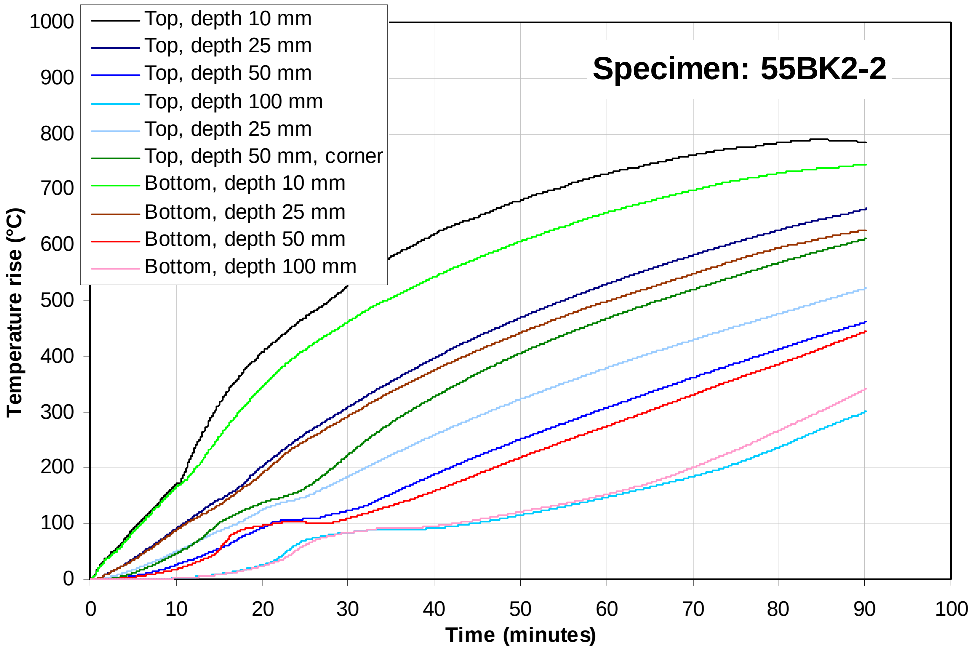

Figure A.38 Temperatures in specimen 55BK2-2.

Concrete 55BK4

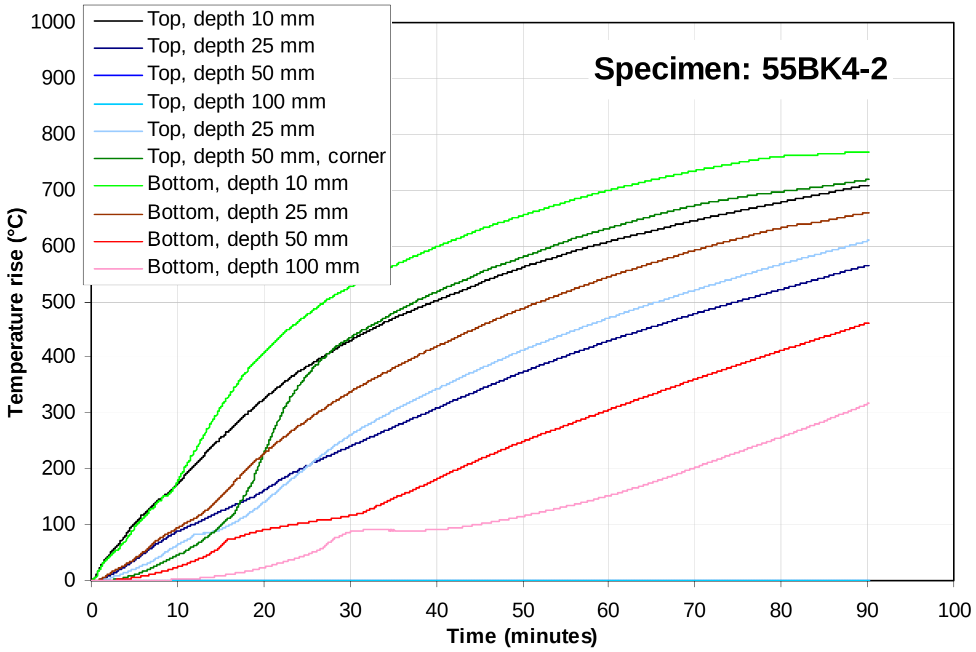

Figure A.39 Temperatures in specimen 55BK4-2.

Concrete 55BR0

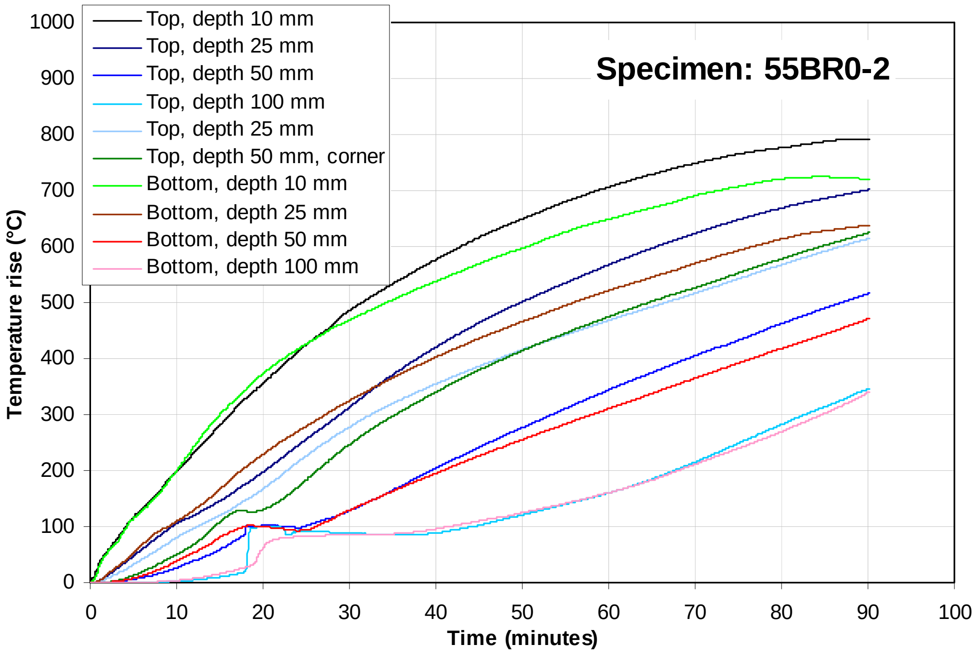

Figure A.40 Temperatures in specimen 55BR0-2.

Concrete 70BK0

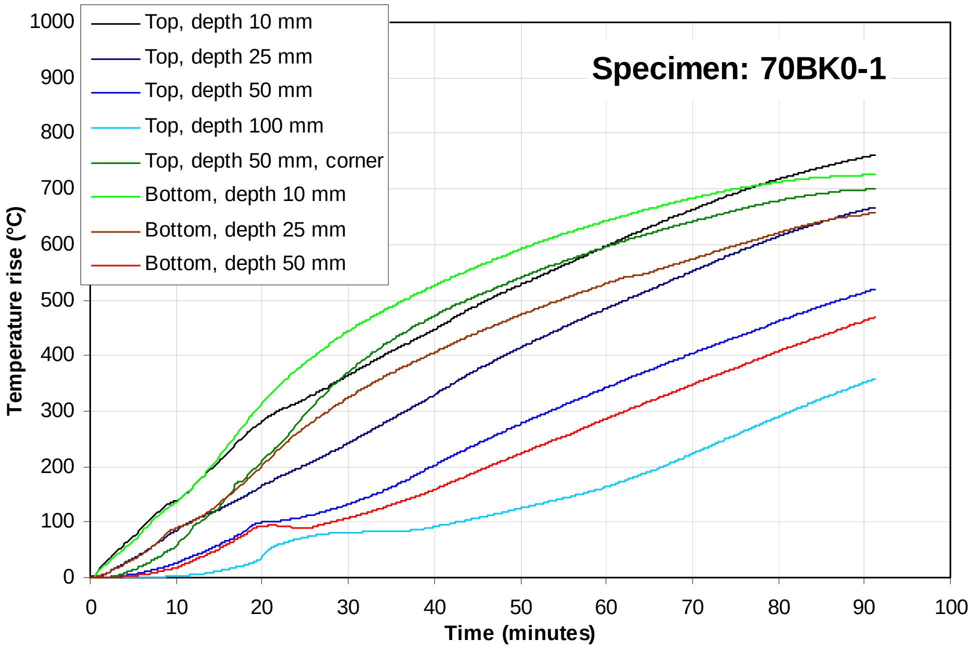

Figure A.41 Temperatures in specimen 70BK0-1.

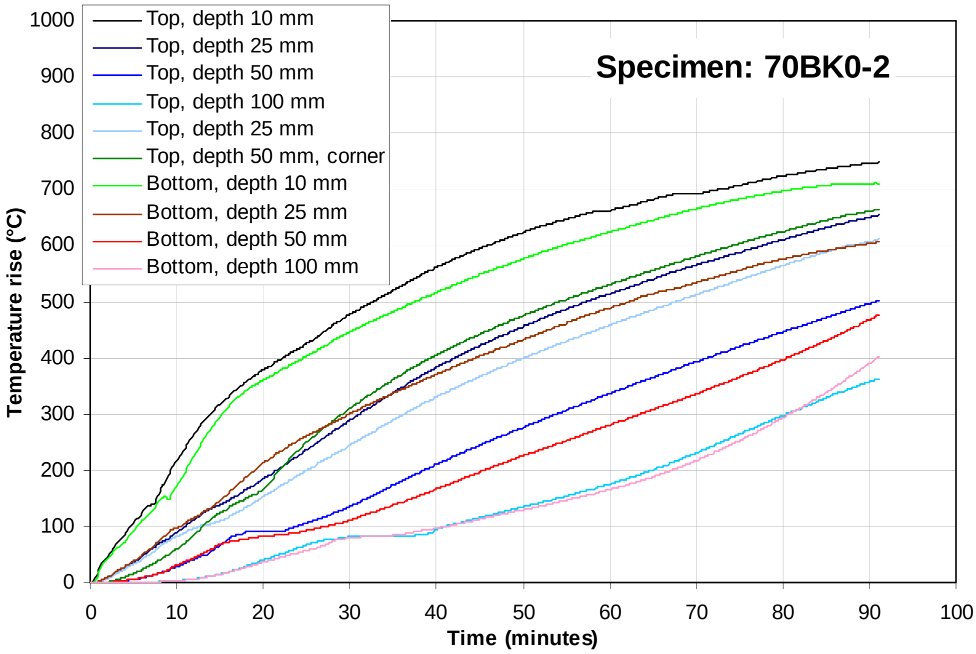

Figure A.42 Temperatures in specimen 70BK0-2.

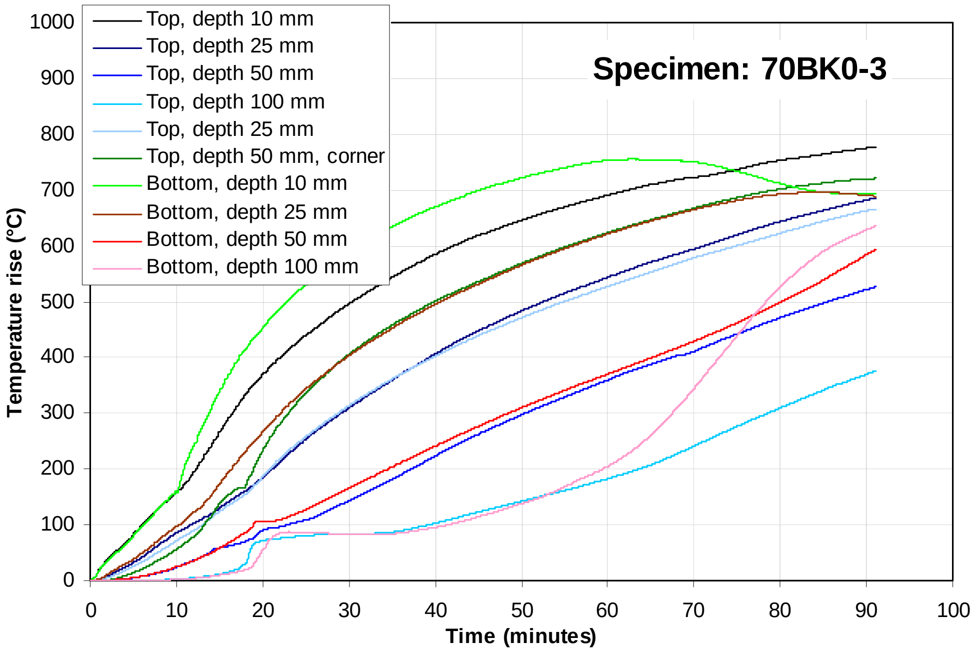

Figure A.43 Temperatures in specimen 70BK0-3.

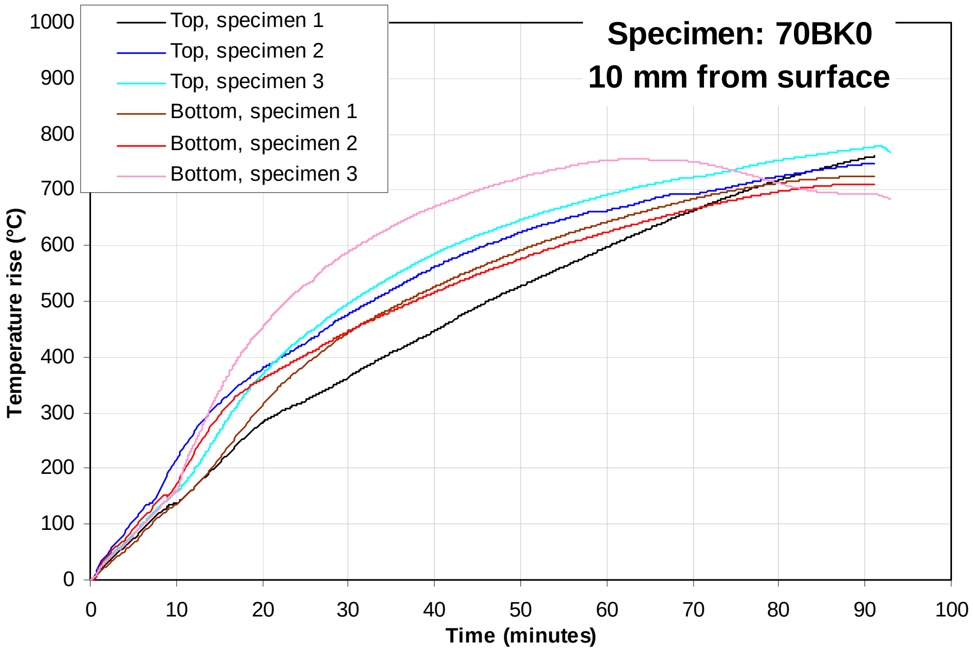

Figure A.44 Temperatures in specimen 70BK0 at 10 mm depth.

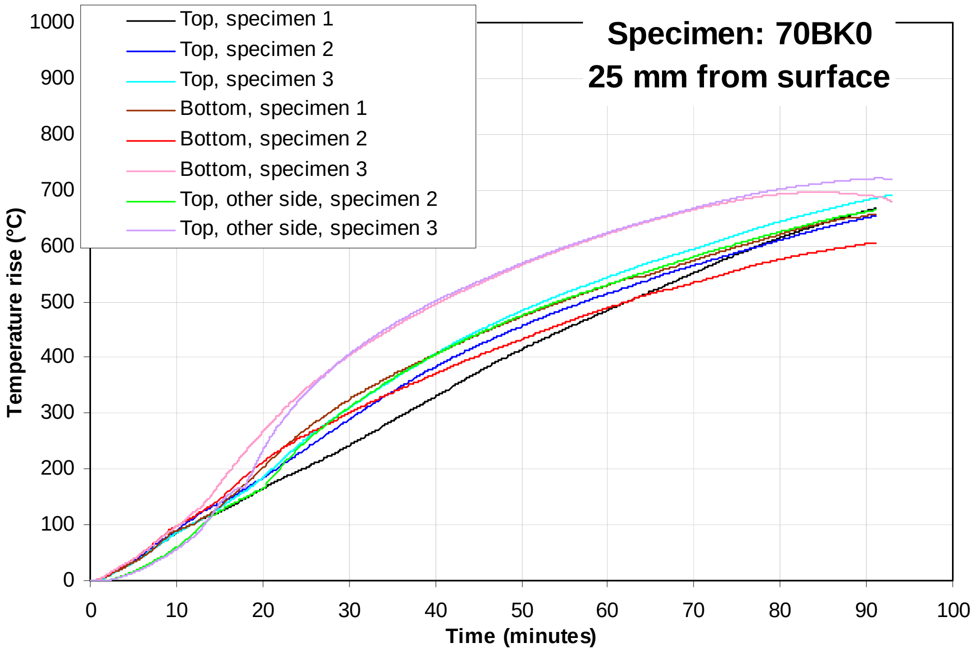

Figure A.45 Temperatures in specimen 70BK0 at 25 mm depth.

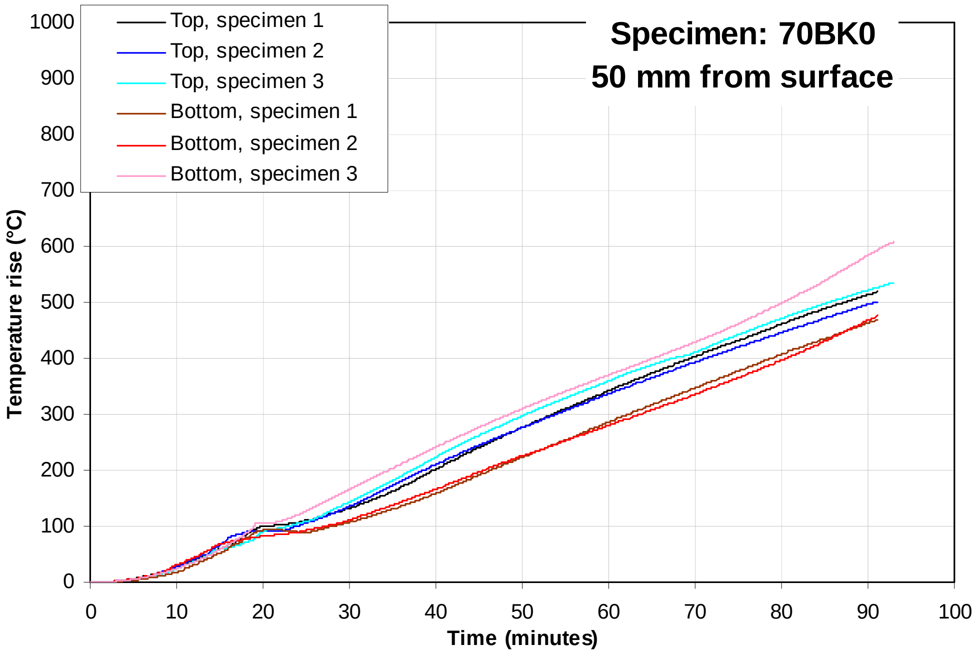

Figure A.46 Temperatures in specimen 70BK0 at 50 mm depth.

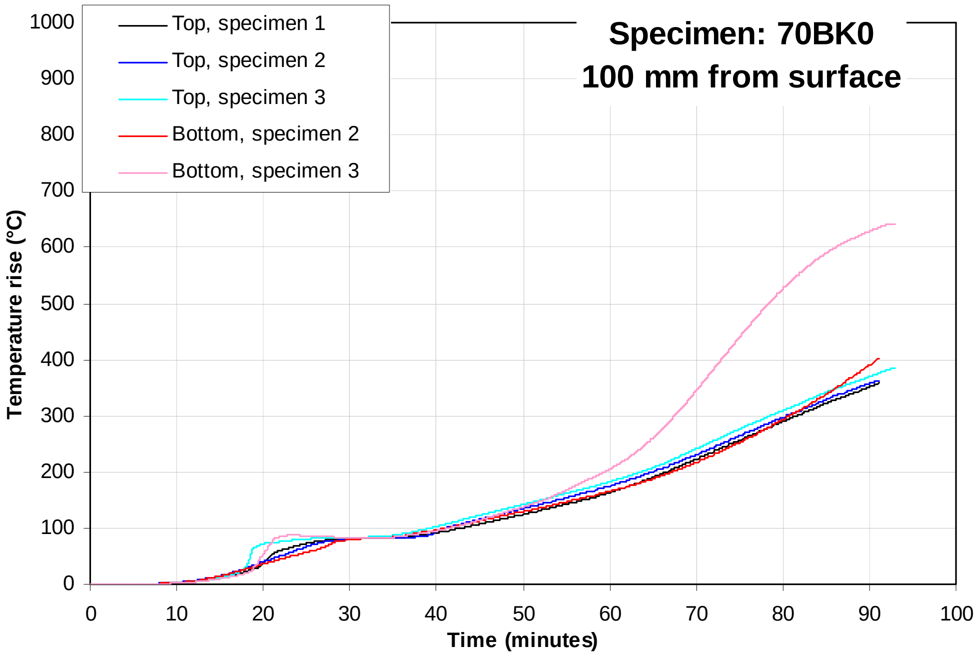

Figure A.47 Temperatures in specimen 70BK0 at 100 mm depth.

Concrete 70BK2

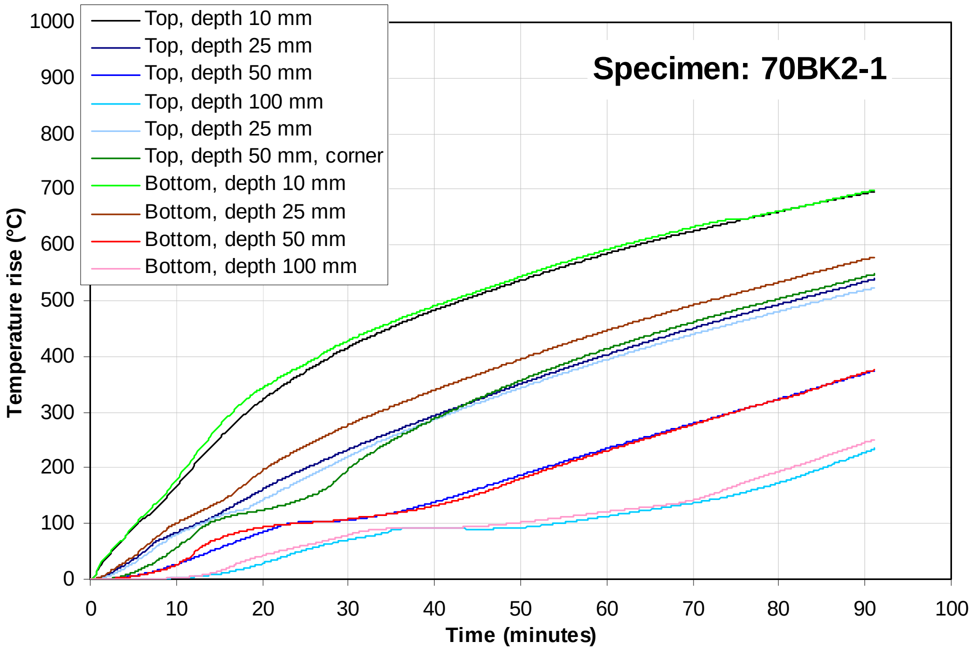

Figure A.48 Temperatures in specimen 70BK2-1.

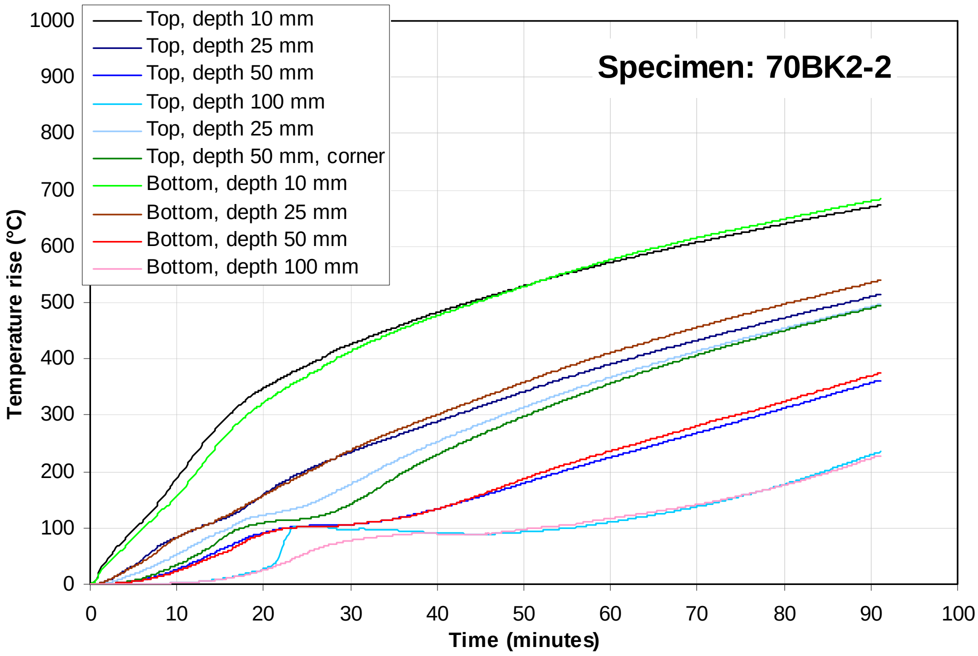

Figure A.49 Temperatures in specimen 70BK2-2.

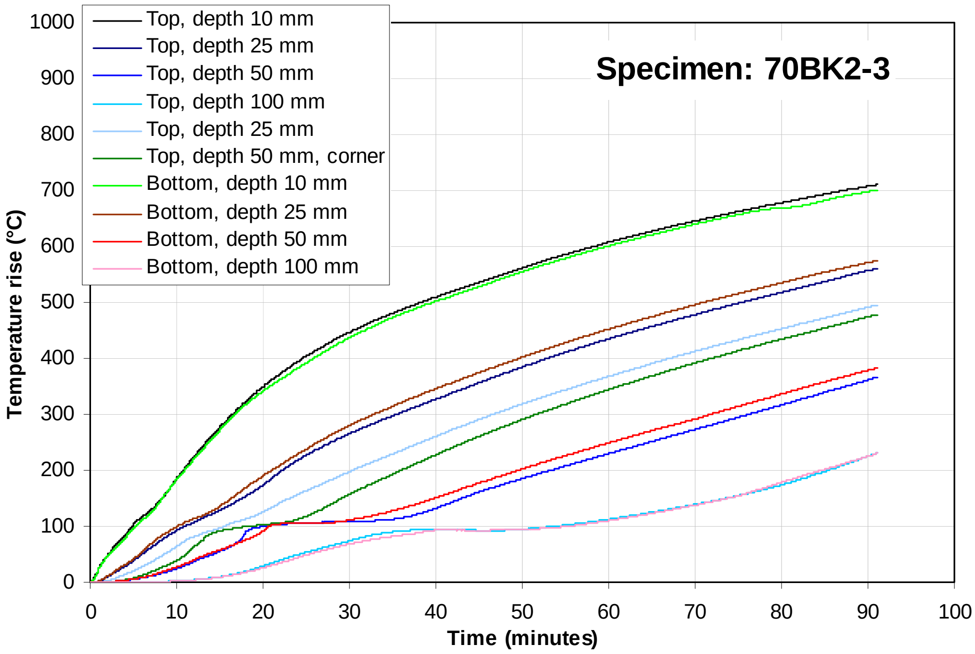

Figure A.50 Temperatures in specimen 70BK2-3.

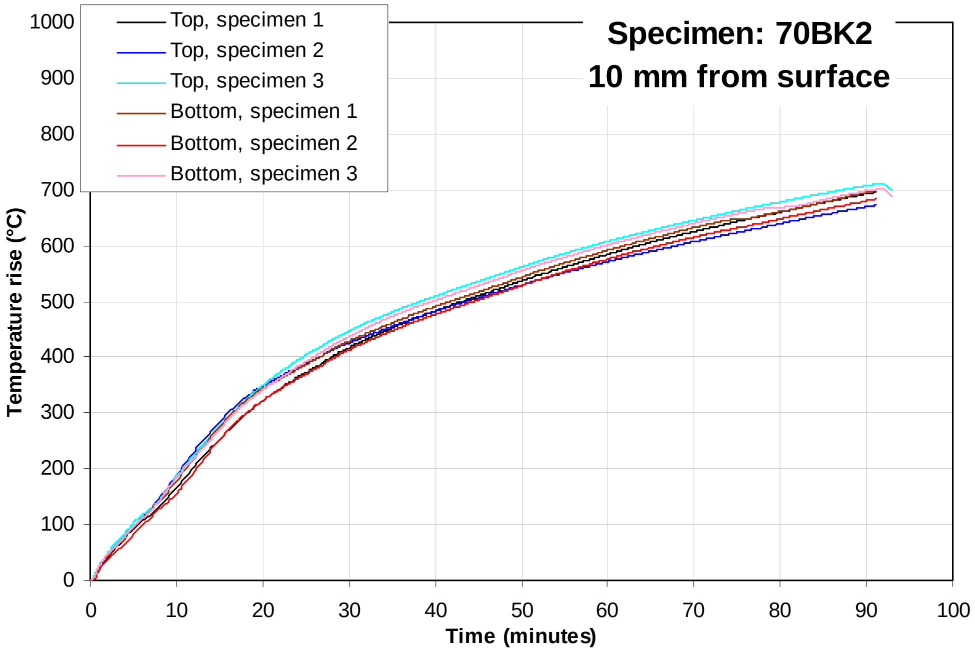

Figure A.51 Temperatures in specimen 70BK2 at 10 mm depth.

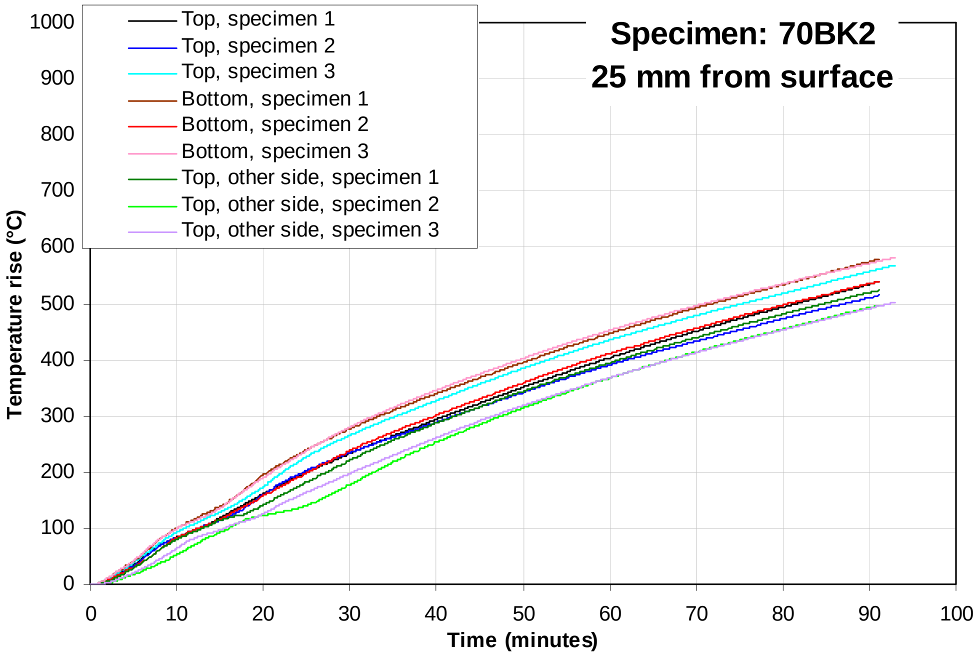

Figure A.52 Temperatures in specimen 70BK2 at 25 mm depth.

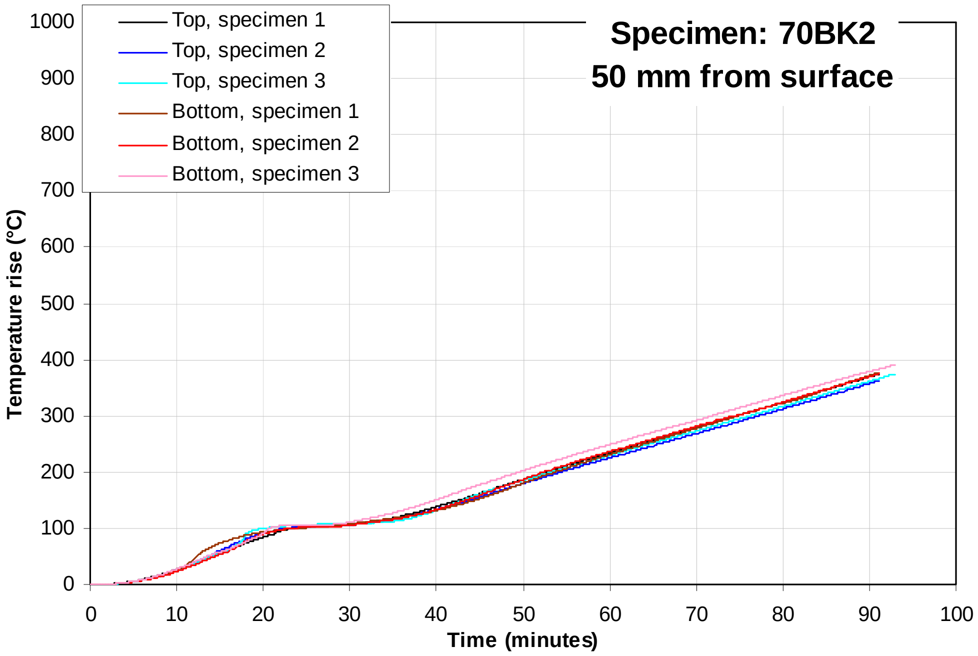

Figure A.53 Temperatures in specimen 70BK2 at 50 mm depth.

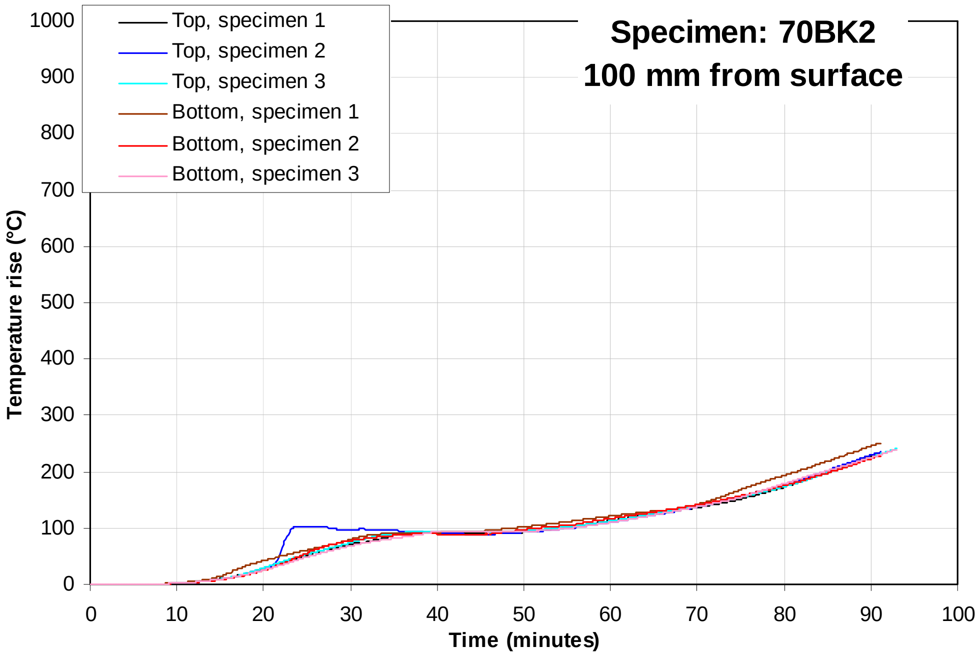

Figure A.54 Temperatures in specimen 70BK2 at 100 mm depth.

Concrete 70BK4

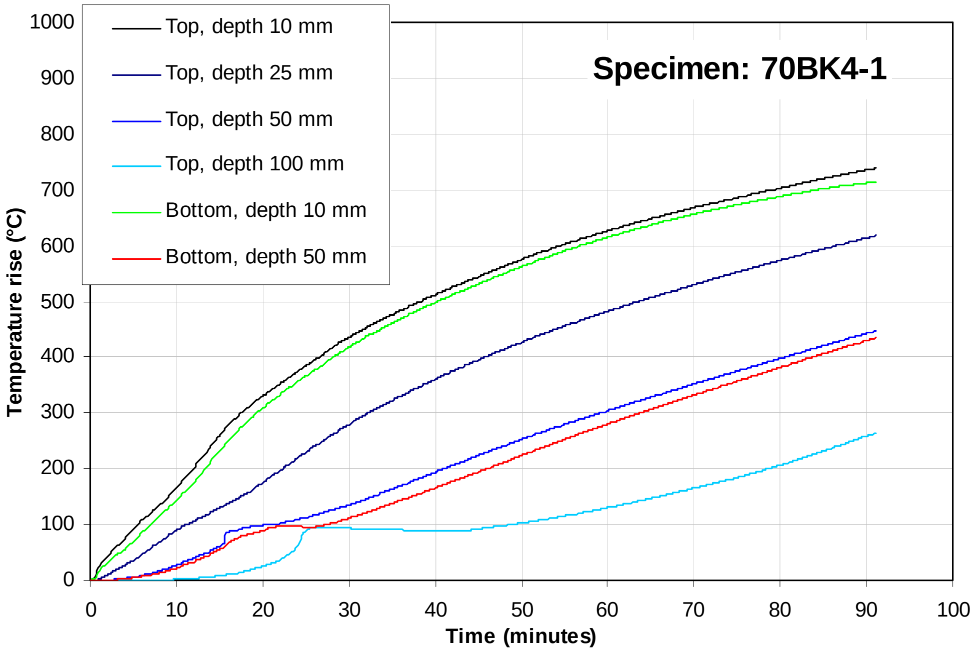

Figure A.55 Temperatures in specimen 70BK4-1.

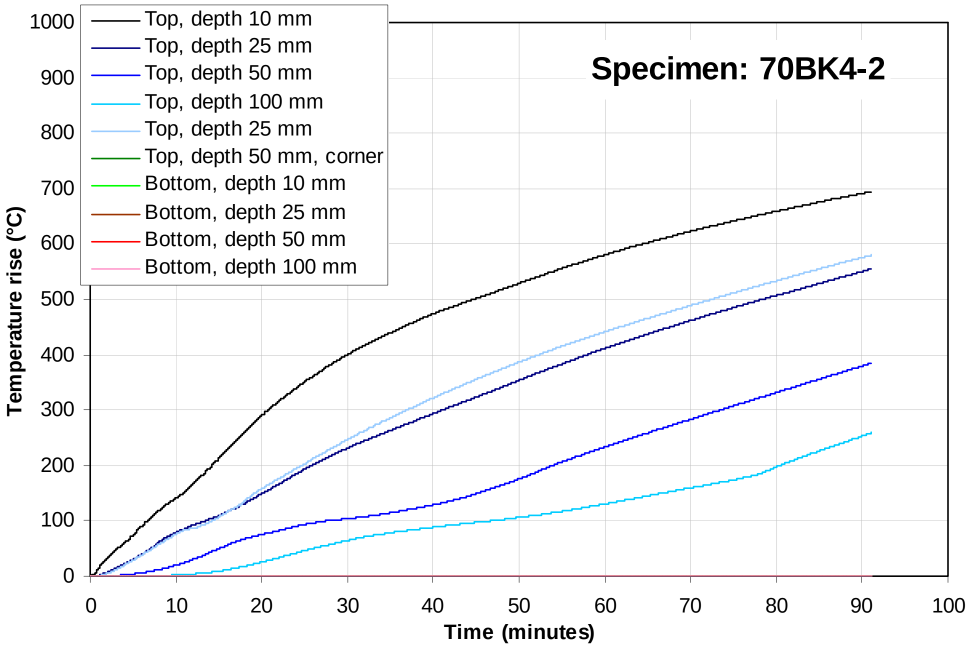

Figure A.56 Temperatures in specimen 70BK4-2.

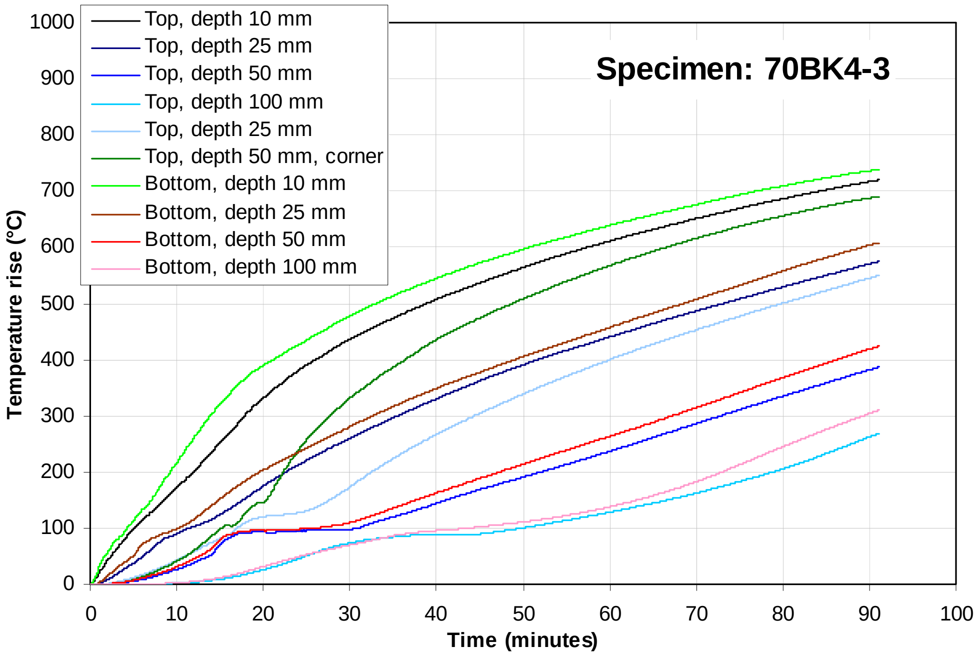

Figure A.57 Temperatures in specimen 70BK4-3.

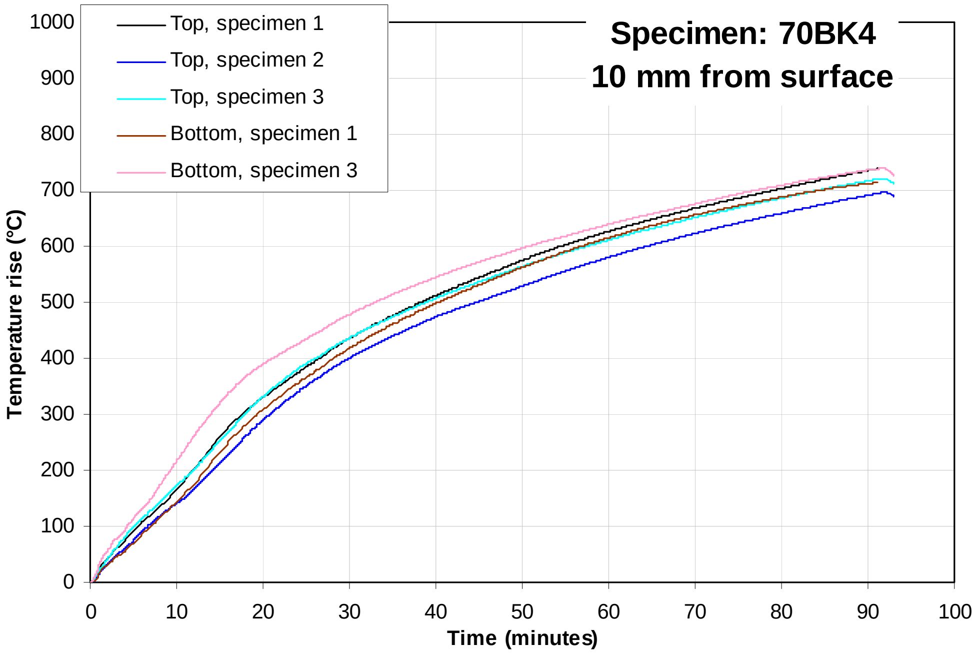

Figure A.58 Temperatures in specimen 70BK4 at 10 mm depth.

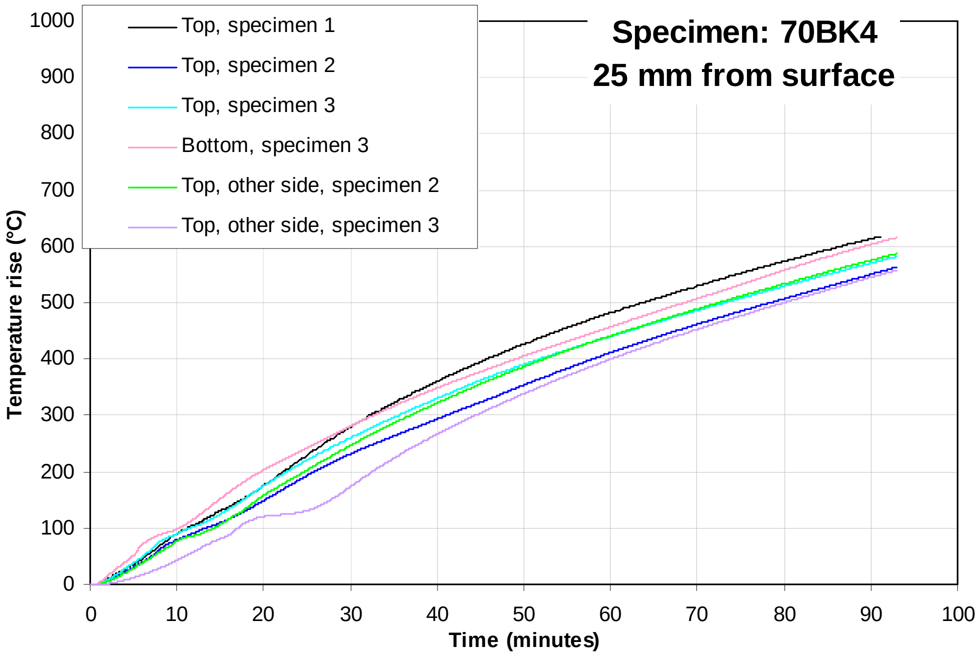

Figure A.59 Temperatures in specimen 70BK4 at 25 mm depth.

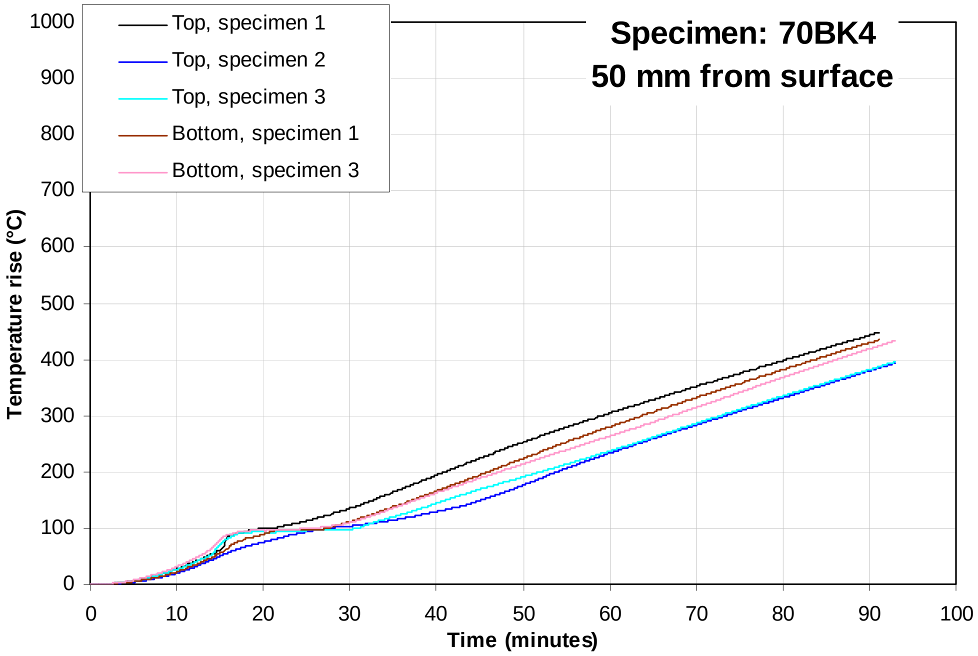

Figure A.60 Temperatures in specimen 70BK4 at 50 mm depth.

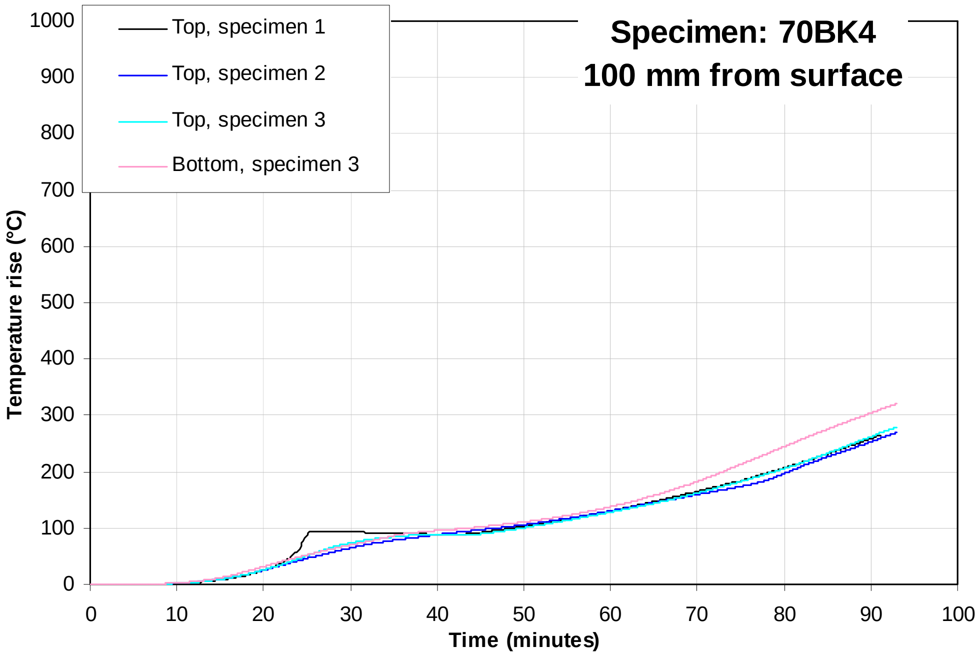

Figure A.61 Temperatures in specimen 70BK4 at 100 mm depth.

Concrete 70BG0

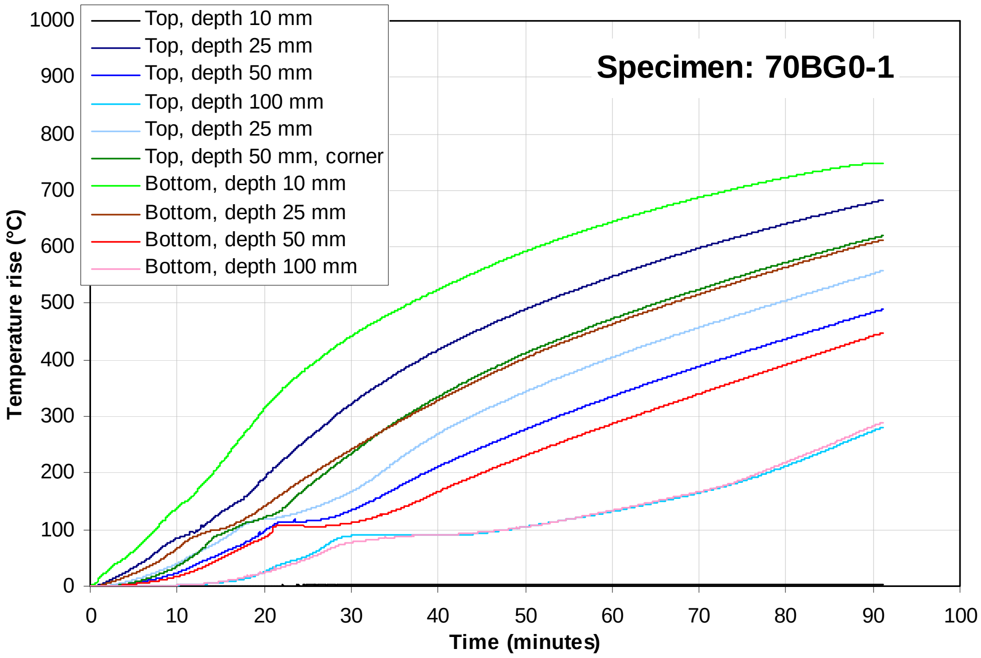

Figure A.62 Temperatures in specimen 70BG0-1.

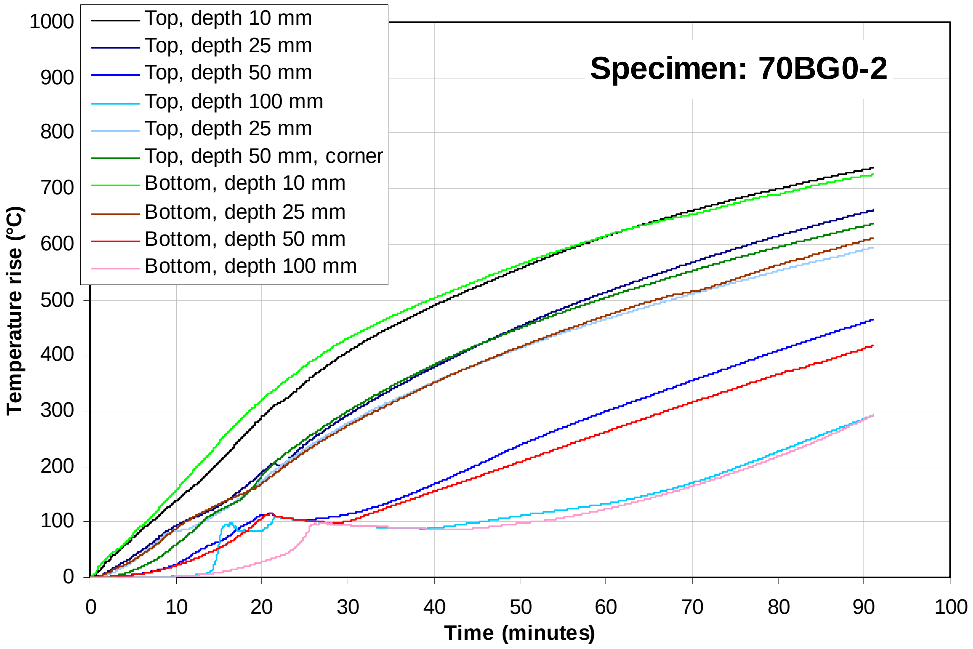

Figure A.63 Temperatures in specimen 70BG0-2.

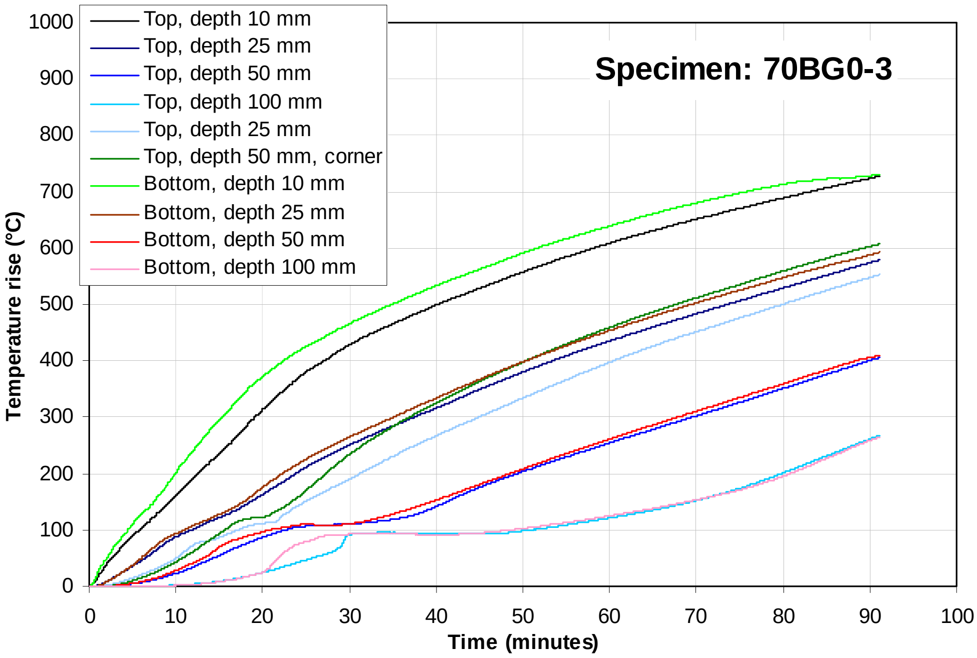

Figure A.64 Temperatures in specimen 70BG0-3.

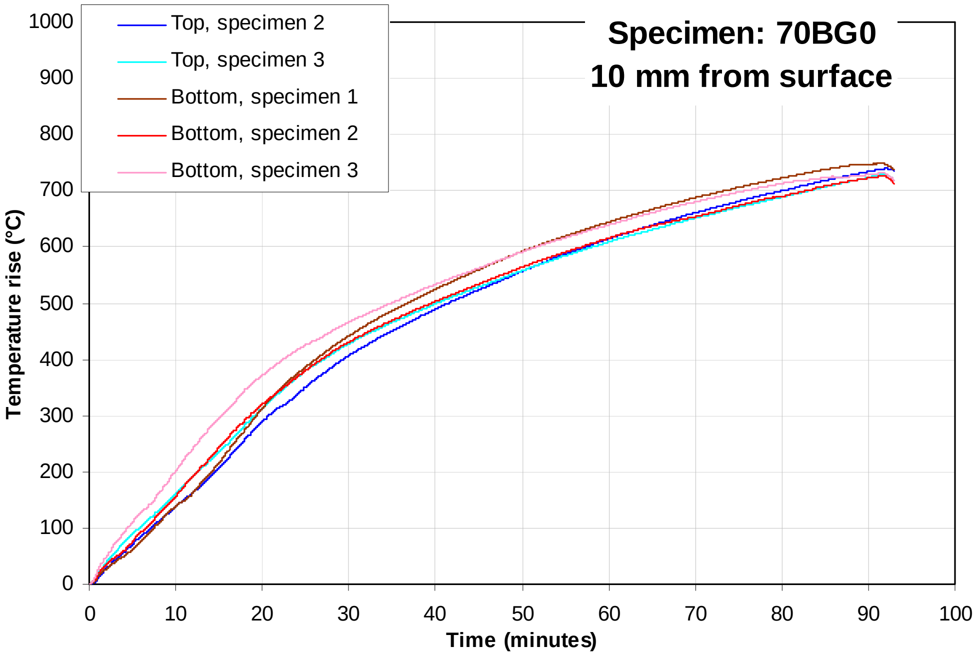

Figure A.65 Temperatures in specimen 70BG0 at 10 mm depth.

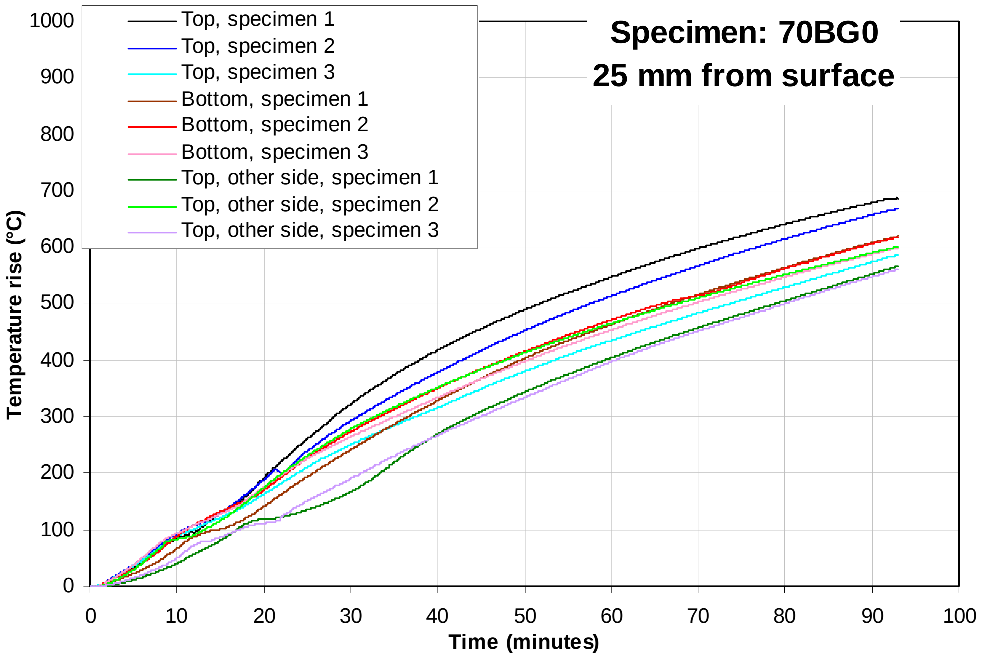

Figure A.66 Temperatures in specimen 70BG0 at 25 mm depth.

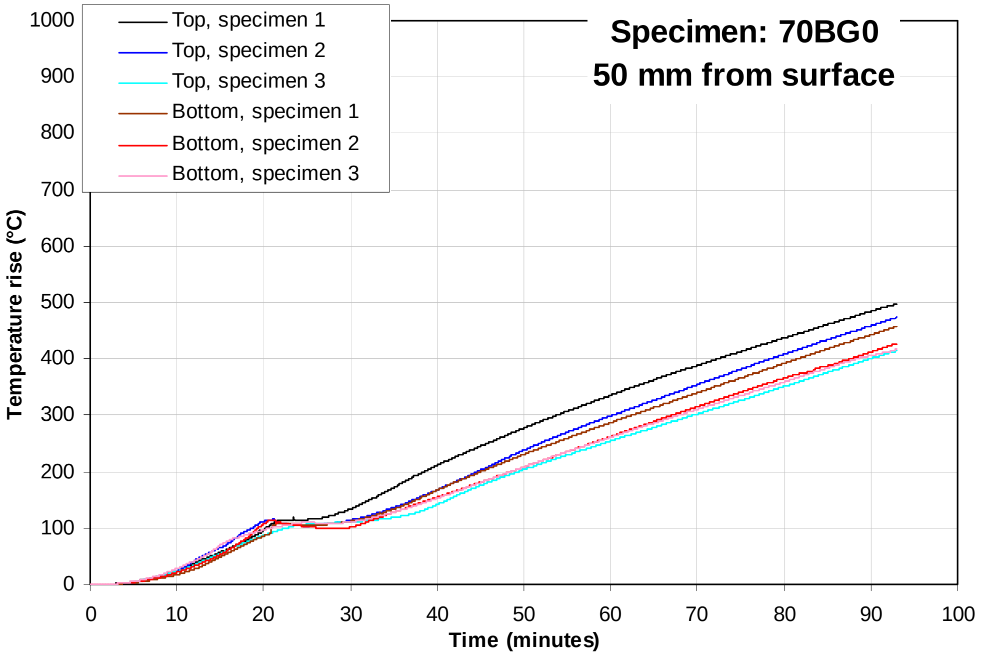

Figure A.67 Temperatures in specimen 70BG0 at 50 mm depth.

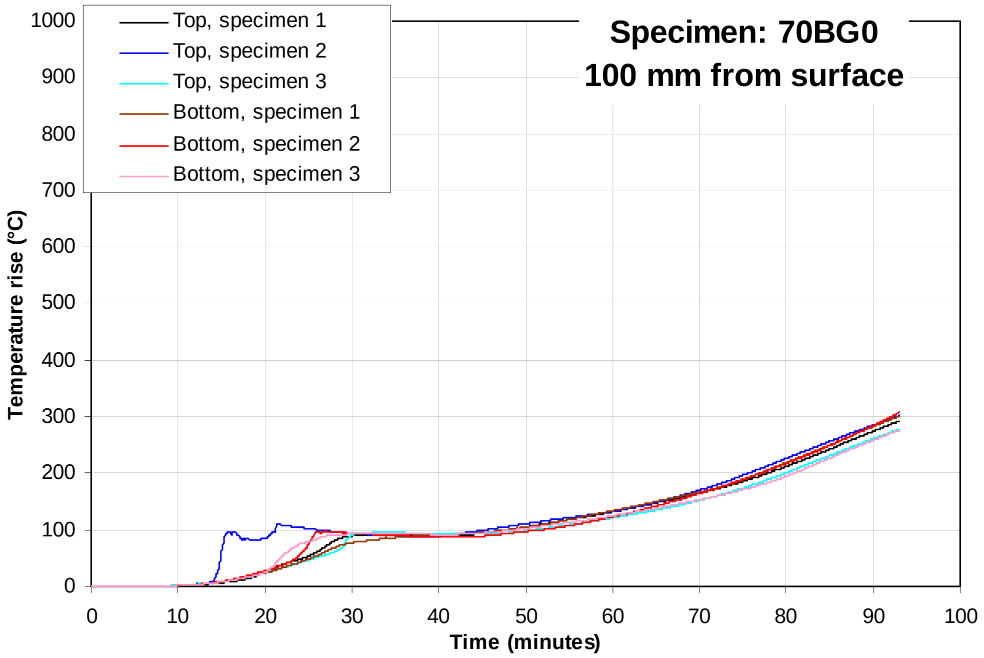

Figure A.68 Temperatures in specimen 70BG0 at 100 mm depth.

Concrete 70BR0

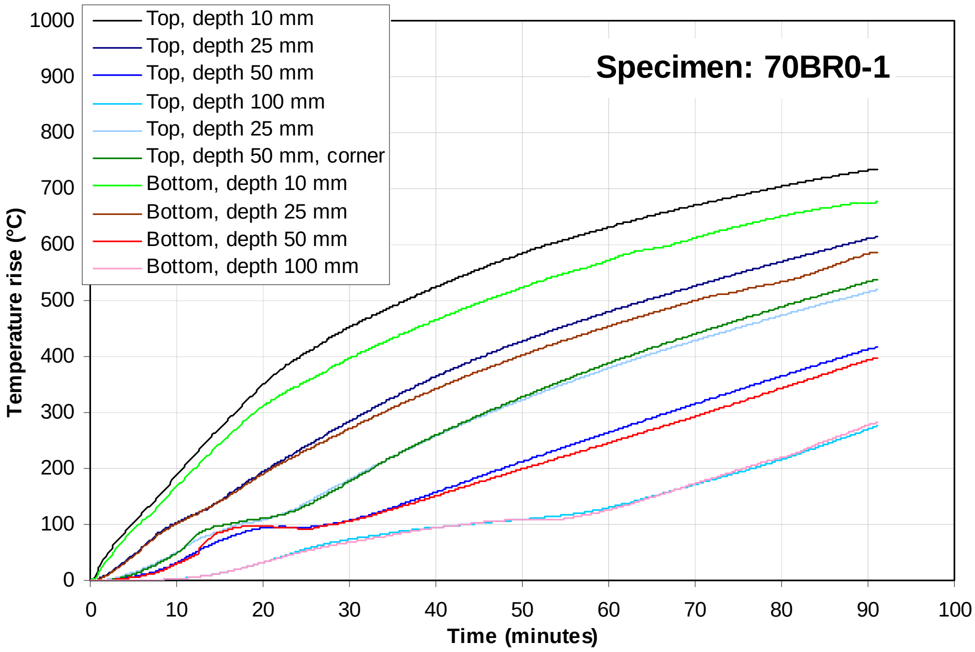

Figure A.69 Temperatures in specimen 70BR0-1.

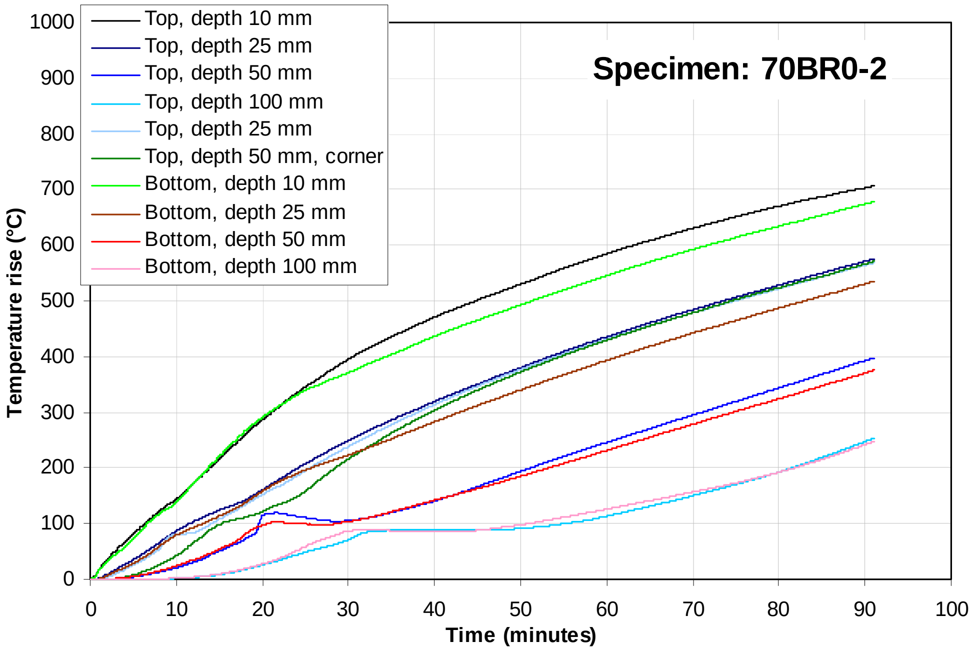

Figure A.70 Temperatures in specimen 70BR0-2.

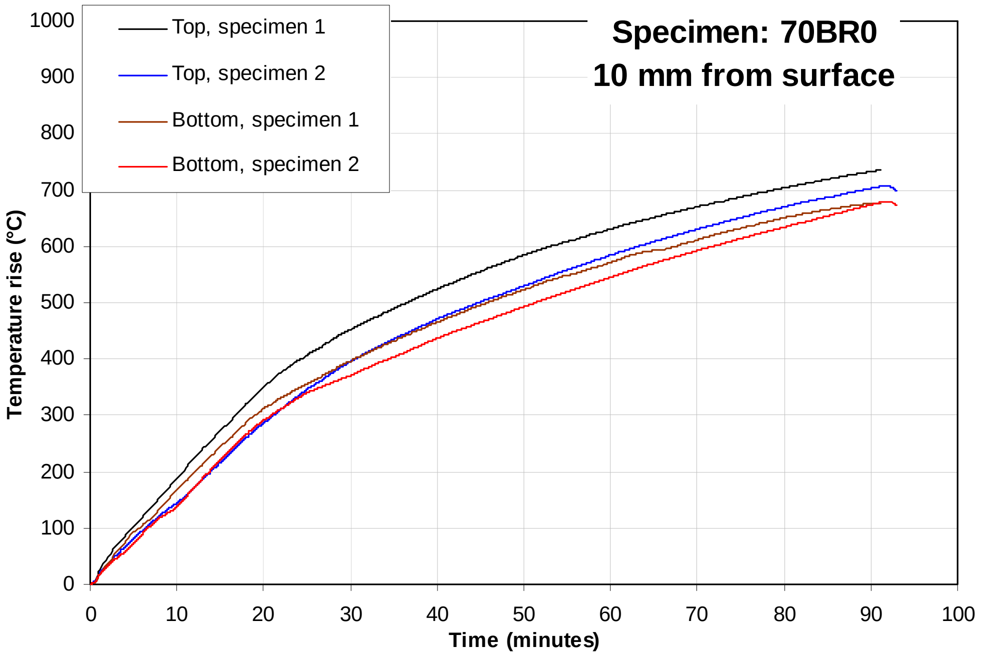

Figure A.71 Temperatures in specimen 70BR0 at 10 mm depth.

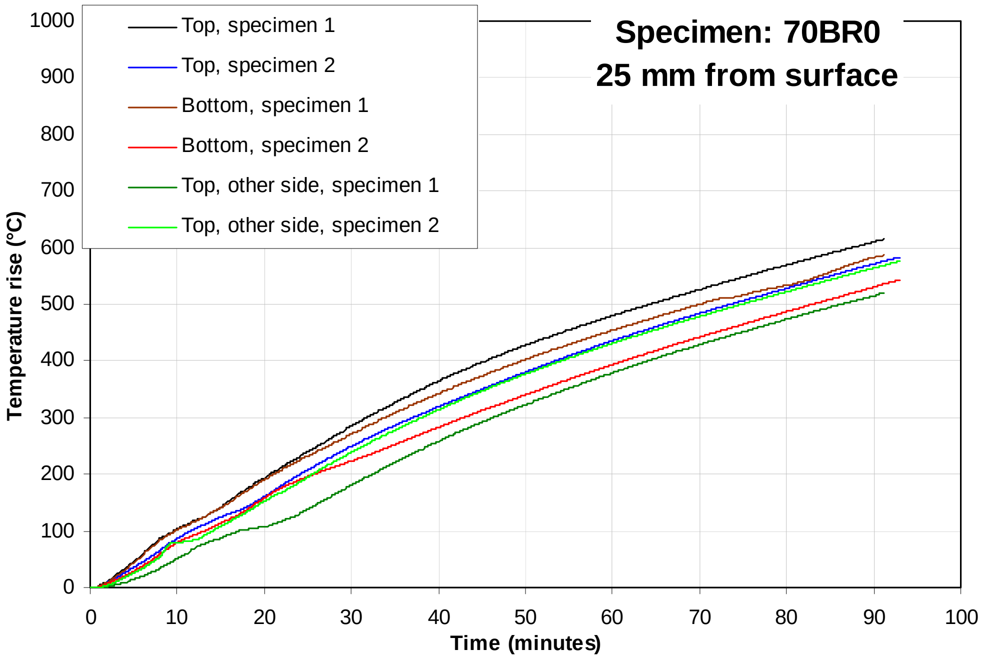

Figure A.72 Temperatures in specimen 70BR0 at 25 mm depth.

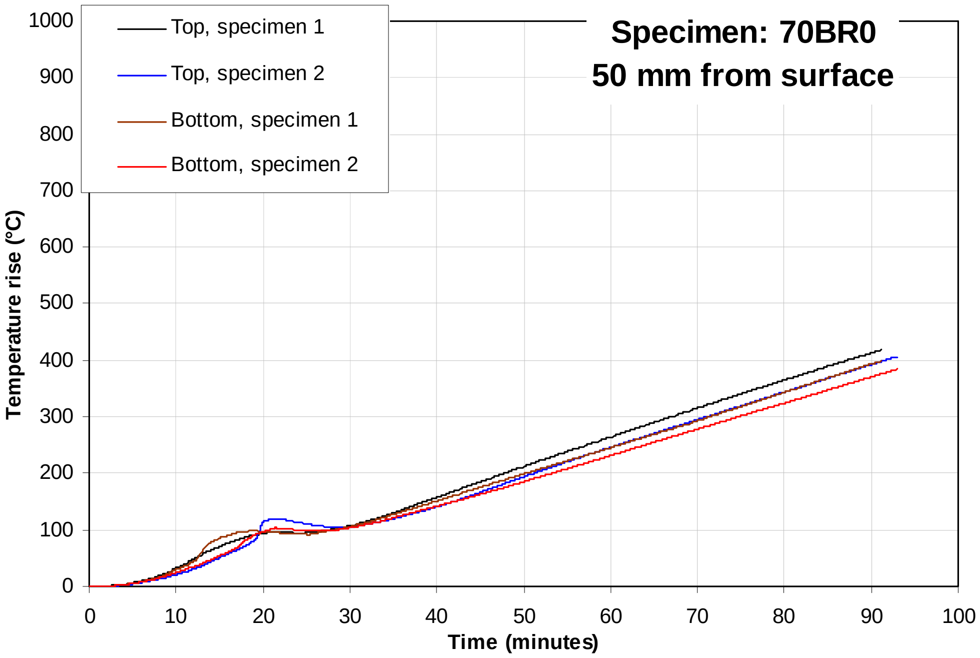

Figure A.73 Temperatures in specimen 70BR0 at 50 mm depth.

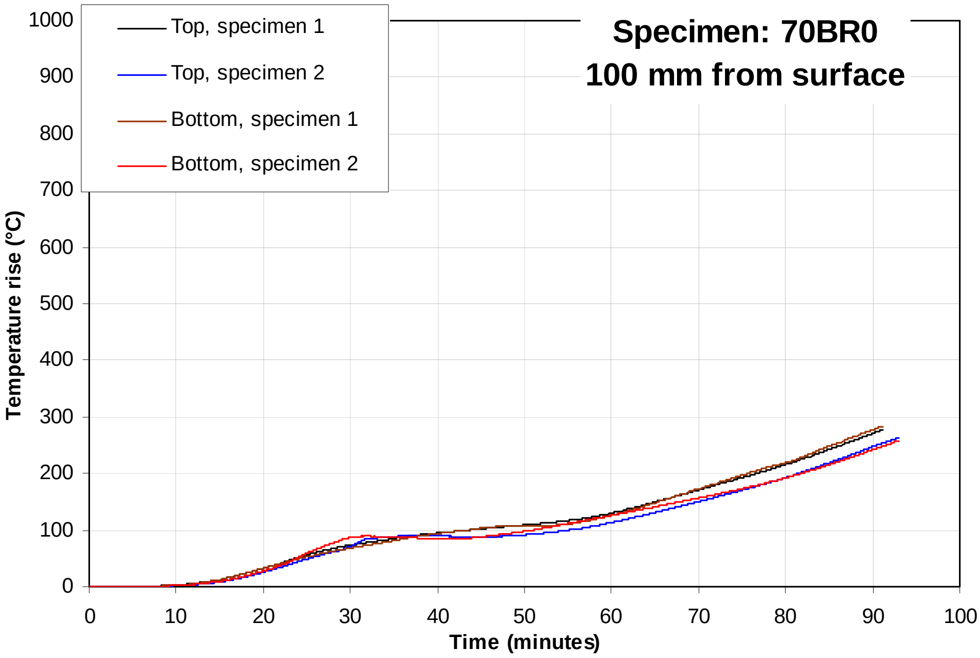

Figure A.74 Temperatures in specimen 70BR0 at 100 mm depth.

Lars Boström

The performance of some self compacting concretes when exposed to fire

- Appendix B -
Photos of test specimens

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Appendix B - Photos of test specimens

Test specimens before furnace test

Figure B.1 Test specimens in the furnace before test.

Test specimens during furnace test

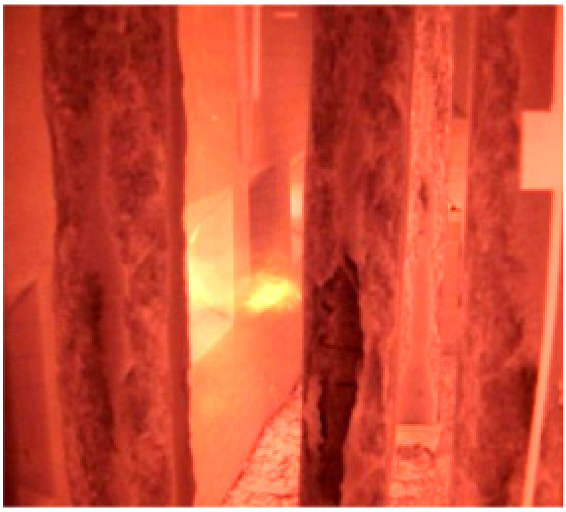

Figure B.2 Test specimens in furnace during test.

Test series 1 - HC-curve

General view after test

Figure B.3 Test specimens 40AK0-1, 40AK2-1 and 40AK4-1 from left to right.

Figure B.4 Test specimens 40AG0-1, 40AR0-1 and 40AK0-2 from left to right.

Figure B.5 Test specimens 40AK2-2, 40AK4-2 and 40AG0-2 from left to right.

Figure B.6 Test specimens 40AR0-2, 40AK0-3, 40AK2-3 and 40AG0-3 from left to right.

Concrete 40AK0

Figure B.7 Test specimen 40AK0-1.

Figure B.8 Test specimen 40AK0-2.

Figure B.9 Test specimen 40AK0-3.

Concrete 40AK2

Figure B.10 Test specimen 40AK2-1.

Figure B.11 Test specimen 40AK2-2.

Figure B.12 Test specimen 40AK2-3.

Concrete 40AK4

Figure B.13 Test specimen 40AK4-1.

Figure B.14 Test specimen 40AK4-2.

Concrete 40AG0

Figure B.15 Test specimen 40AG0-1.

Figure B.16 Test specimen 40AG0-2.

Figure B.17 Test specimen 40AG0-3.

Concrete 40AR0

Figure B.18 Test specimen 40AR0-1.

Figure B.19 Test specimen 40AR0-2.

Test series 2 - Standard fire

General view after test

Figure B.20 Test specimens 40BK0-1, 40BR0-1 and 55BK0-1 from left to right.

Figure B.21 Test specimens 55BK2-1, 55BK4-1 and 55BR0-1 from left to right.

Figure B.22 Test specimens 55BK0-2, 40BR0-2 and 40BK0-2 from left to right.

Figure B.23 Test specimens 55BK2-2, 55BK4-2, 55BR0-2 and 40BK0-3 from left to right.

Concrete 40BK0

Figure B.24 Test specimen 40BK0-1.

Figure B.25 Test specimen 40BK0-2.

Figure B.26 Test specimen 40BK0-3.

Concrete 40BR0

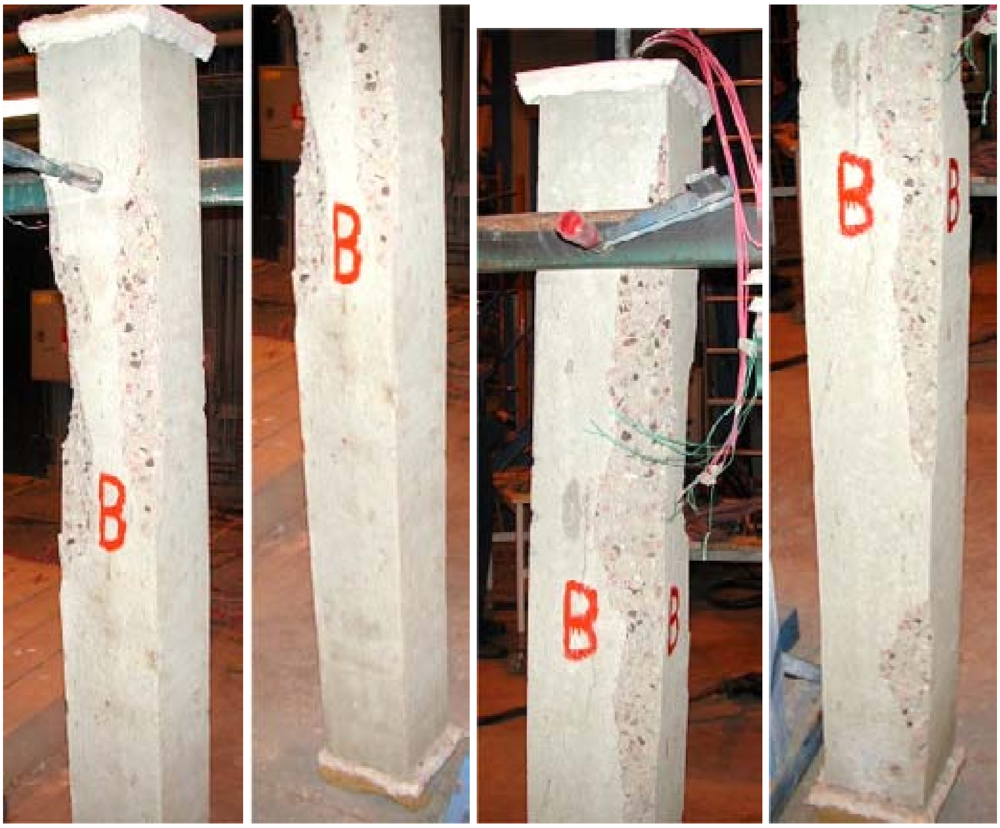

Figure B.27 Test specimen 40BR0-1.

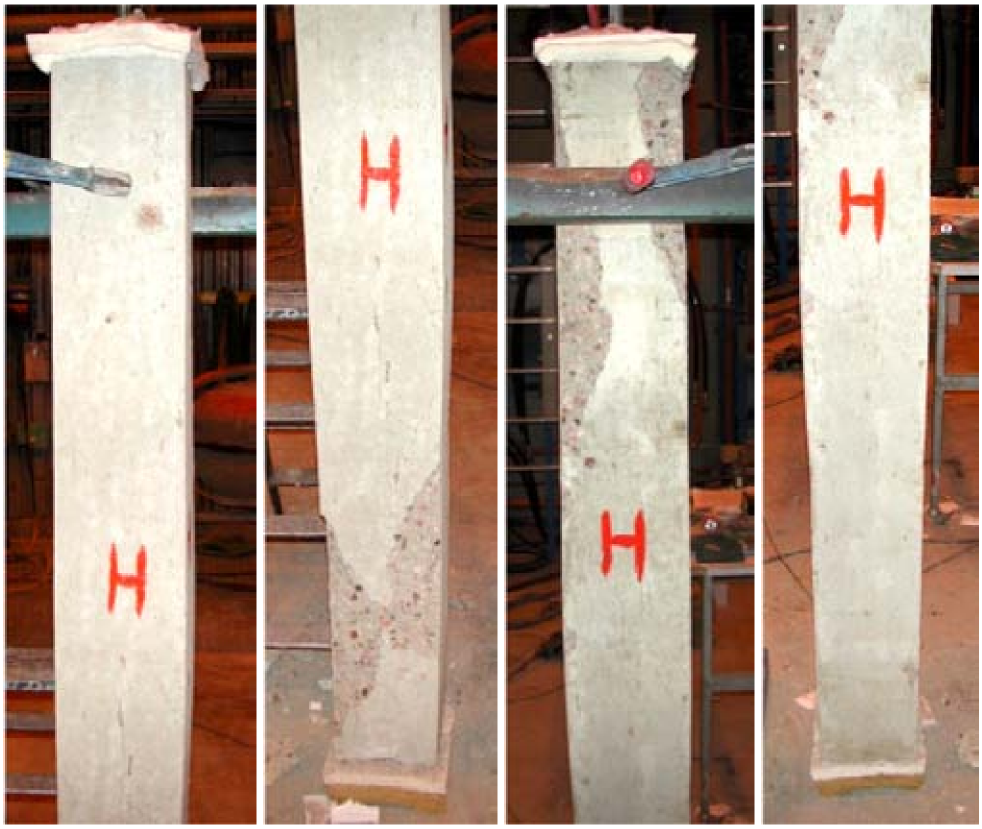

Figure B.28 Test specimen 40BR0-2.

Concrete 55BK0

Figure B.29 Test specimen 55BK0-1.

Figure B.30 Test specimen 55BK0-2.

Concrete 55BK2

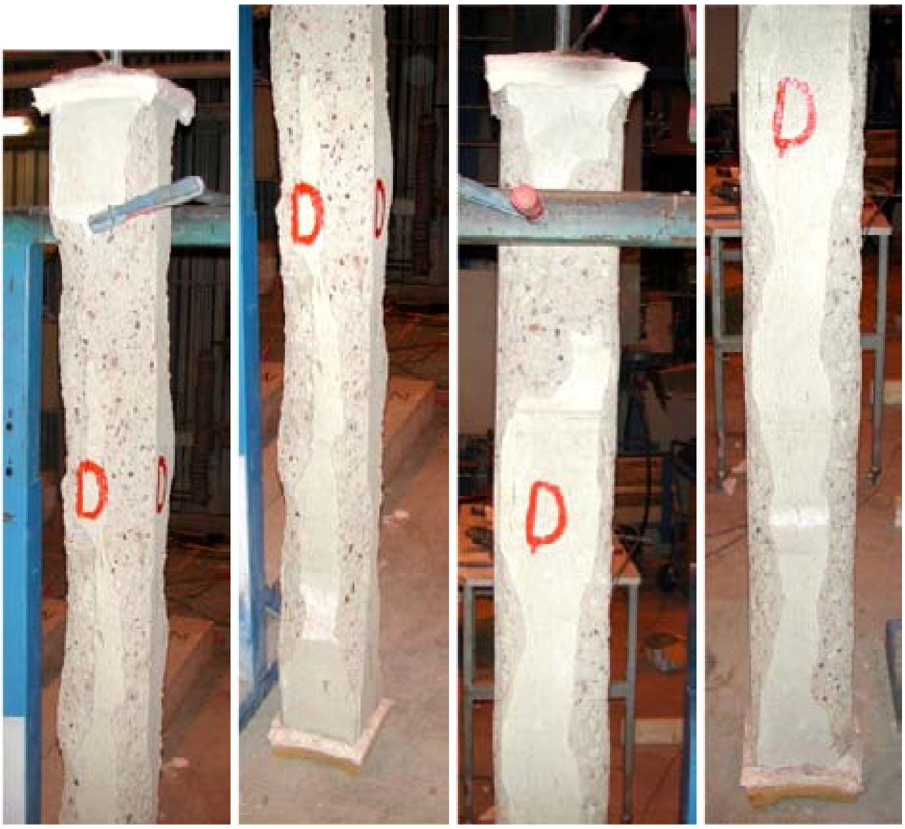

Figure B.31 Test specimen 55BK2-1.

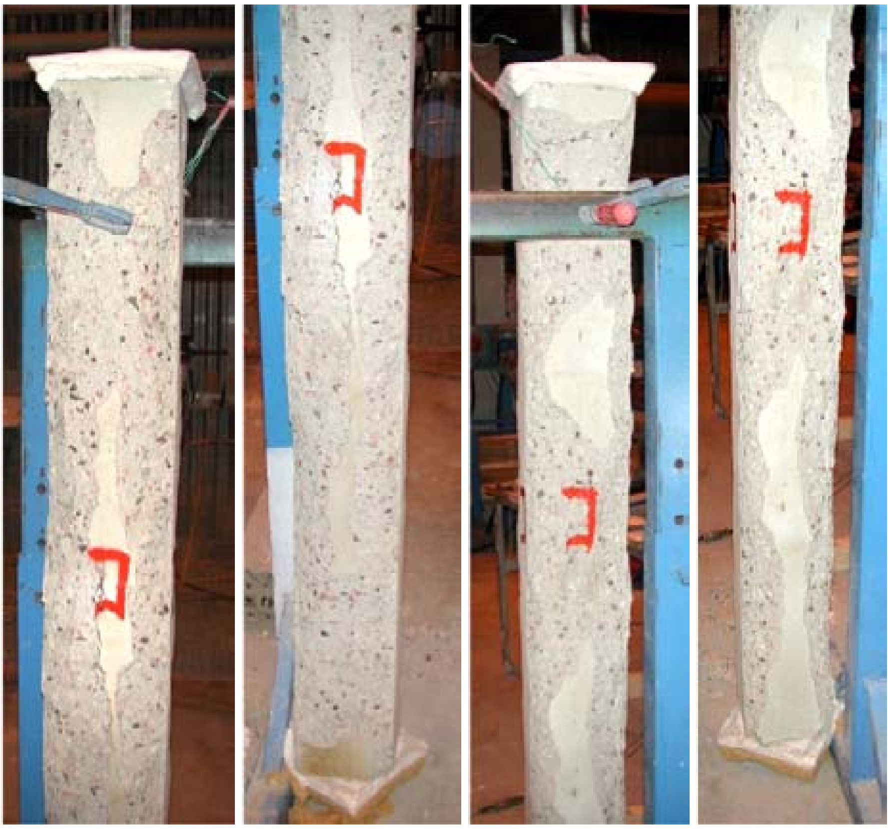

Figure B.32 Test specimen 55BK2-2.

Concrete 55BK4

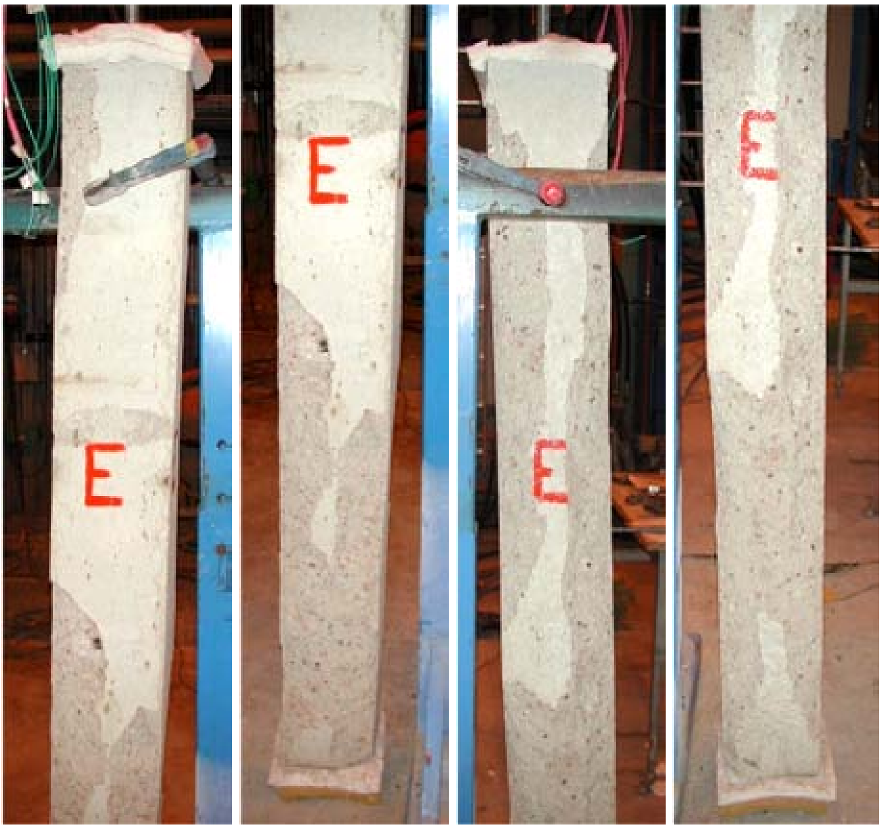

Figure B.33 Test specimen 55BK4-1.

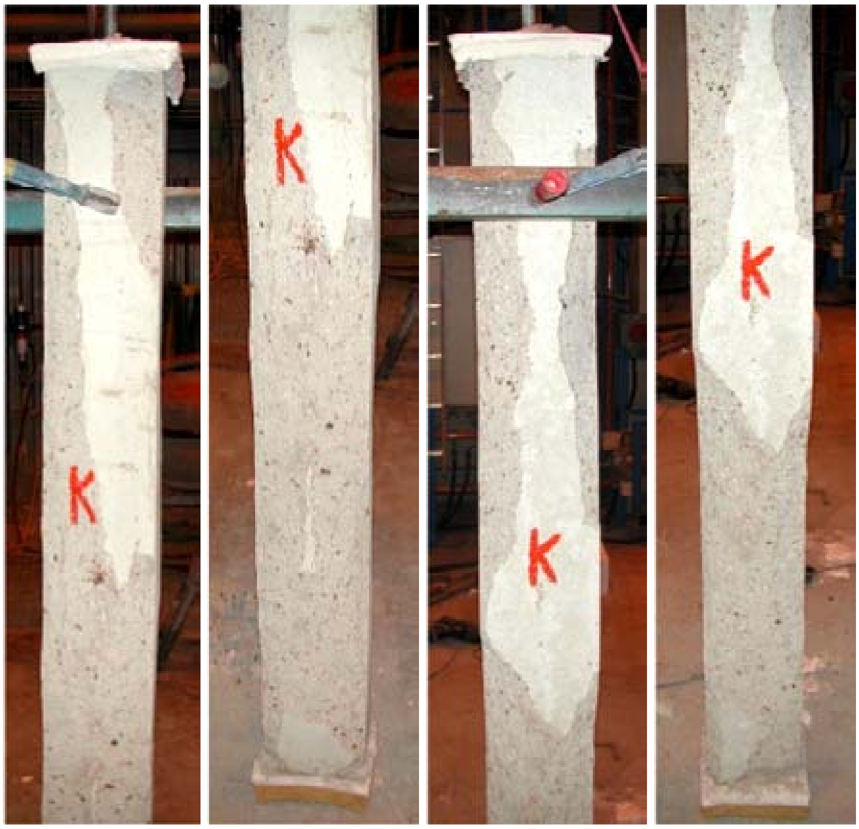

Figure B.34 Test specimen 55BK4-2.

Concrete 55BR0

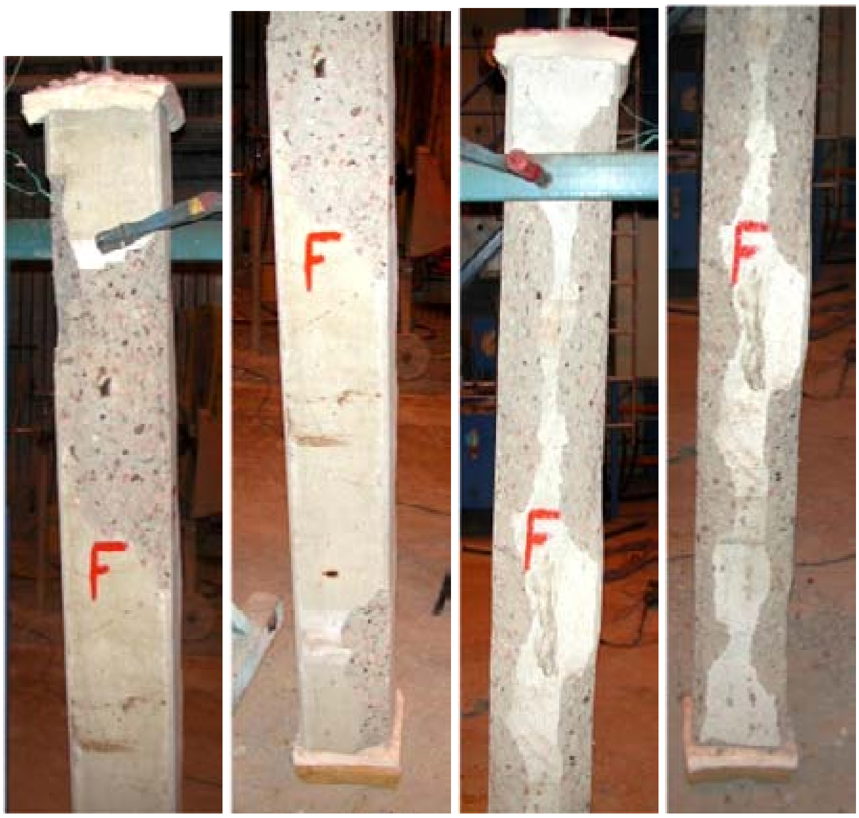

Figure B.35 Test specimen 55BR0-1.

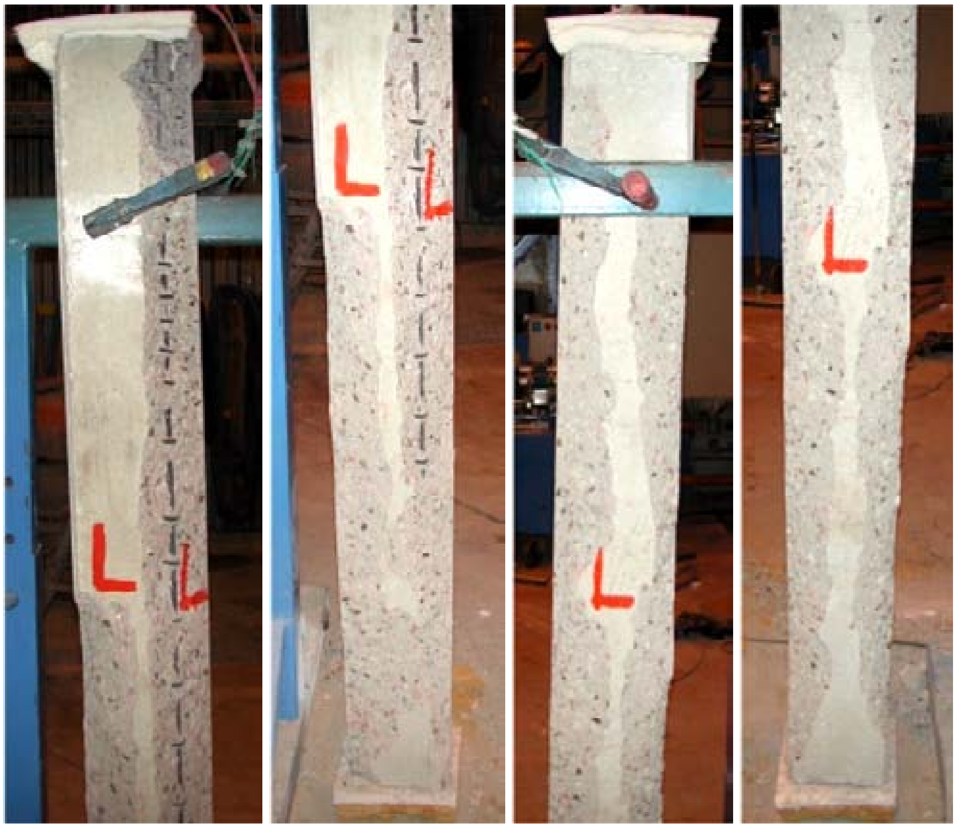

Figure B.36 Test specimen 55BR0-2.

Test series 3 - Standard fire

General view after test

Figure B.37 Test specimens 70BK0-1, 70BK2-1, 70BK4-1 and 70BG0-1 from left to right.

Figure B.38 Test specimens 70BR0-1, 70BK0-2 and 70BK2-2 from left to right.

Figure B.39 Test specimens 70BK4-2, 70BG0-2 and 70BR0-2 from left to right.

Figure B.40 Test specimens 70BK0-3, 70BK2-3, 70BK4-3 and 70BG0-3 from left to right.

Concrete 70BK0

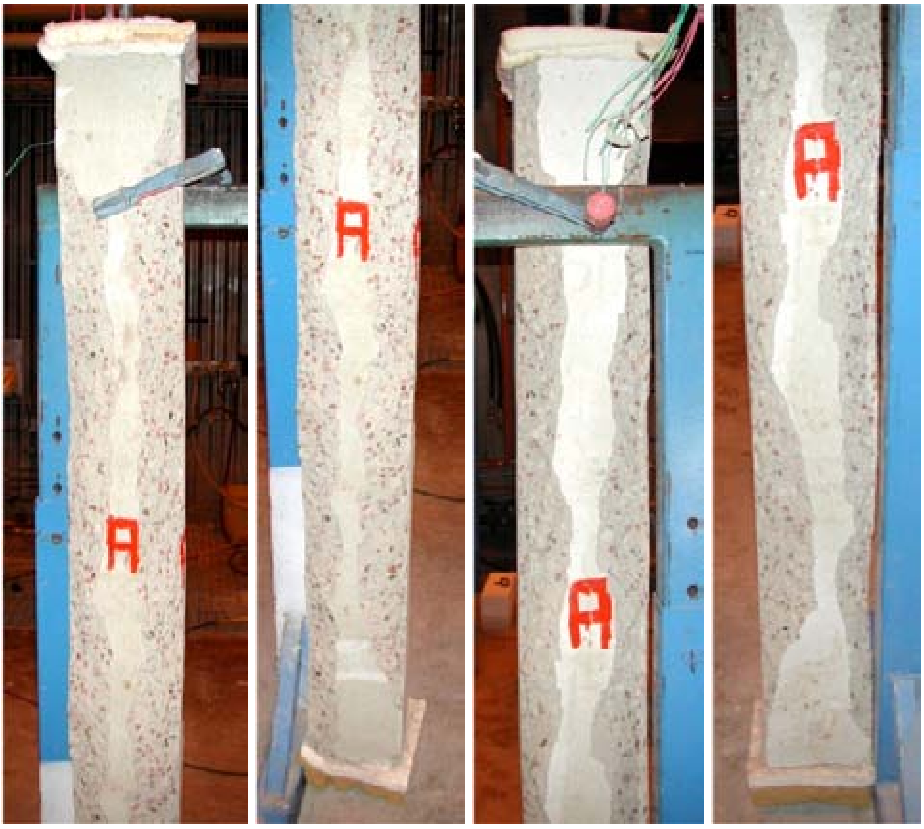

Figure B.41 Test specimen 70BK0-1.

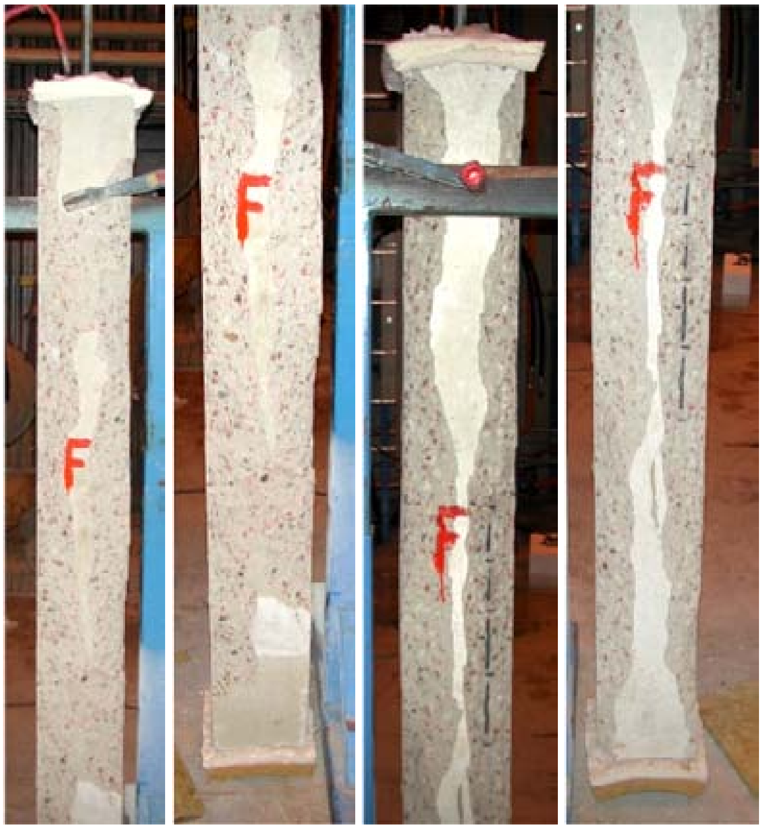

Figure B.42 Test specimen 70BK0-2.

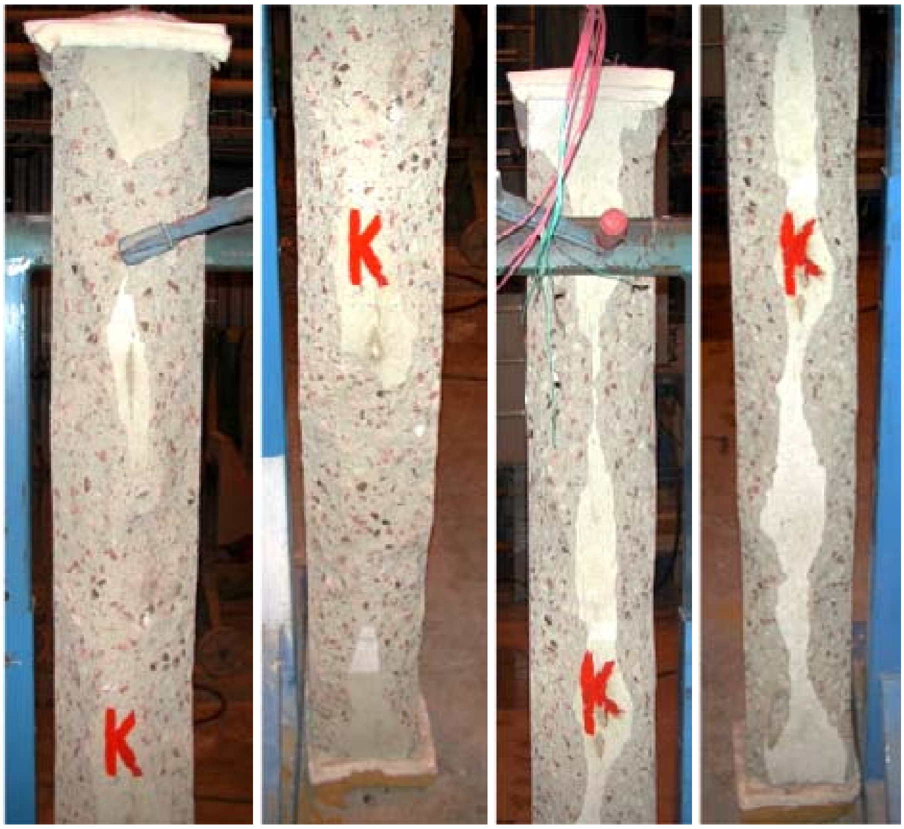

Figure B.43 Test specimen 70BK0-3.

Concrete 70BK2

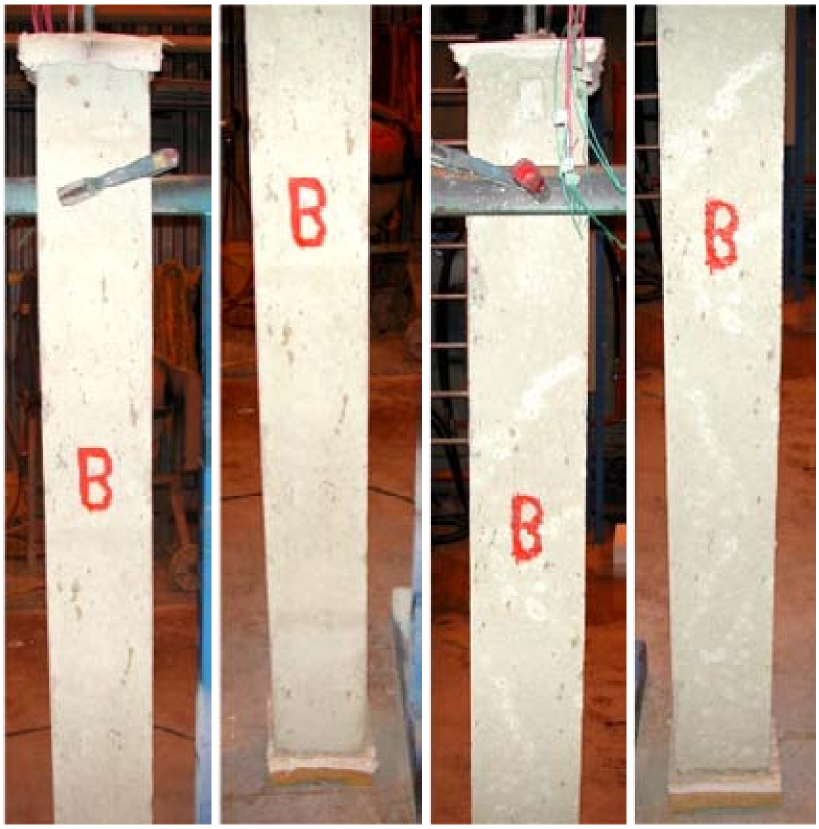

Figure B.44 Test specimen 70BK2-1.

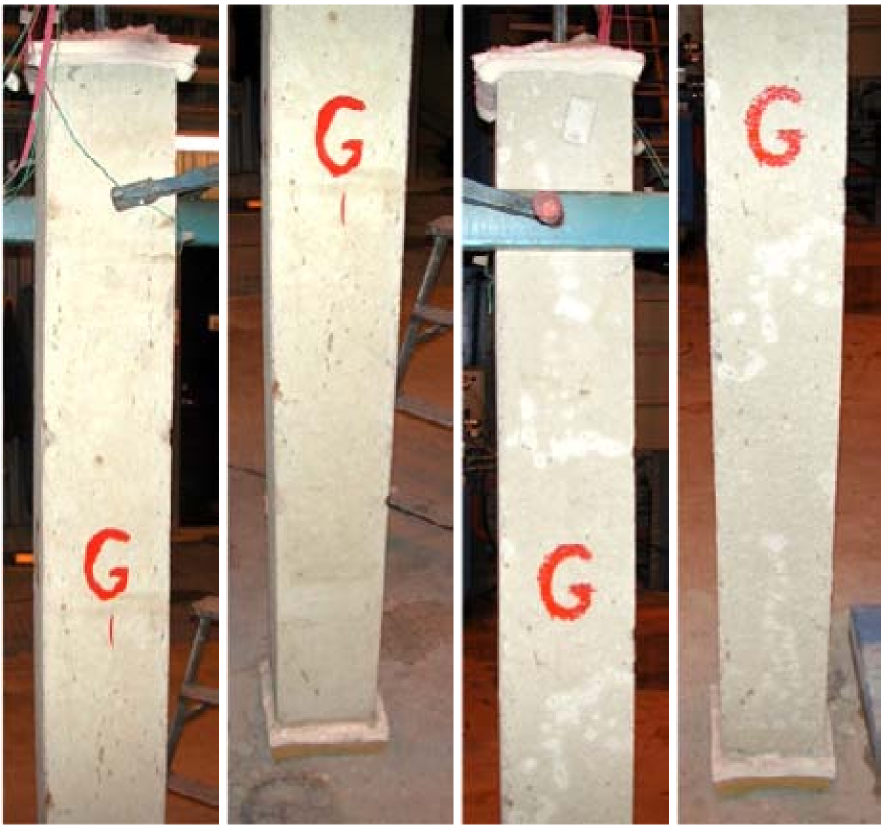

Figure B.45 Test specimen 70BK2-2.

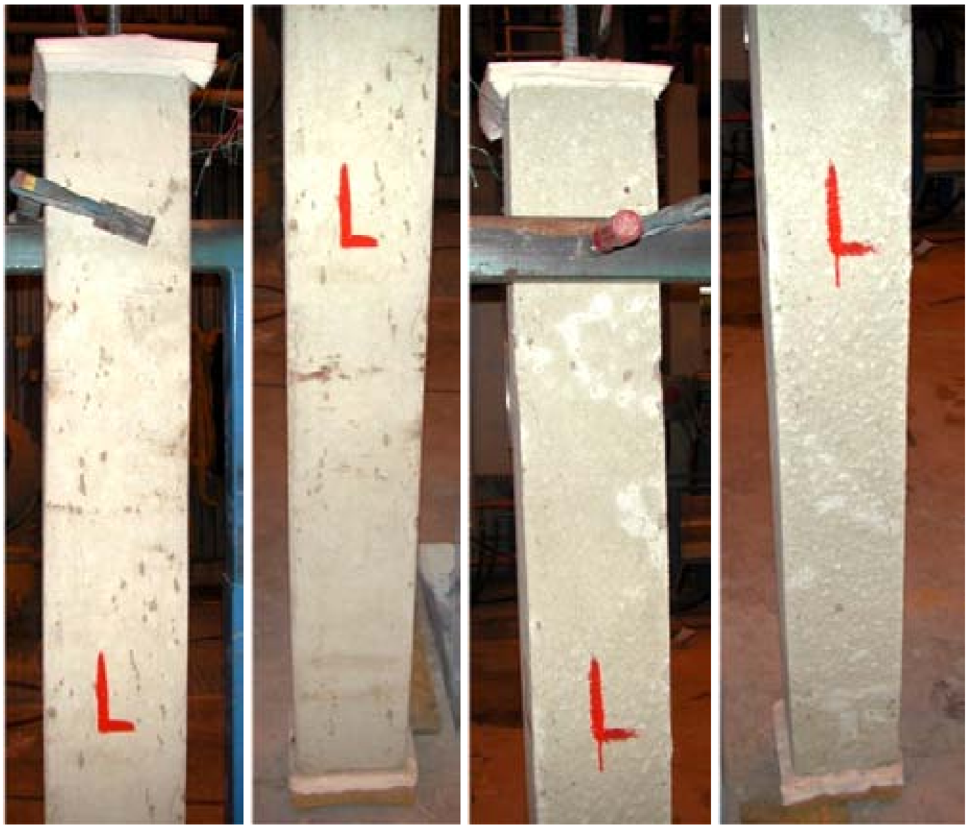

Figure B.46 Test specimen 70BK2-3.

Concrete 70BK4

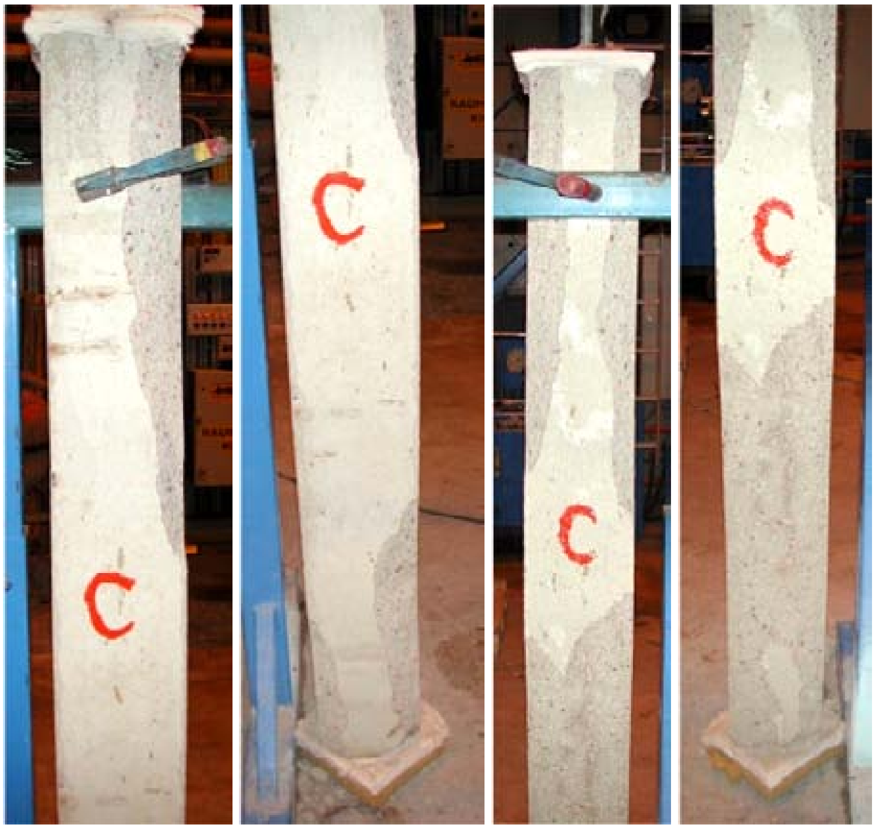

Figure B.47 Test specimen 70BK4-1.

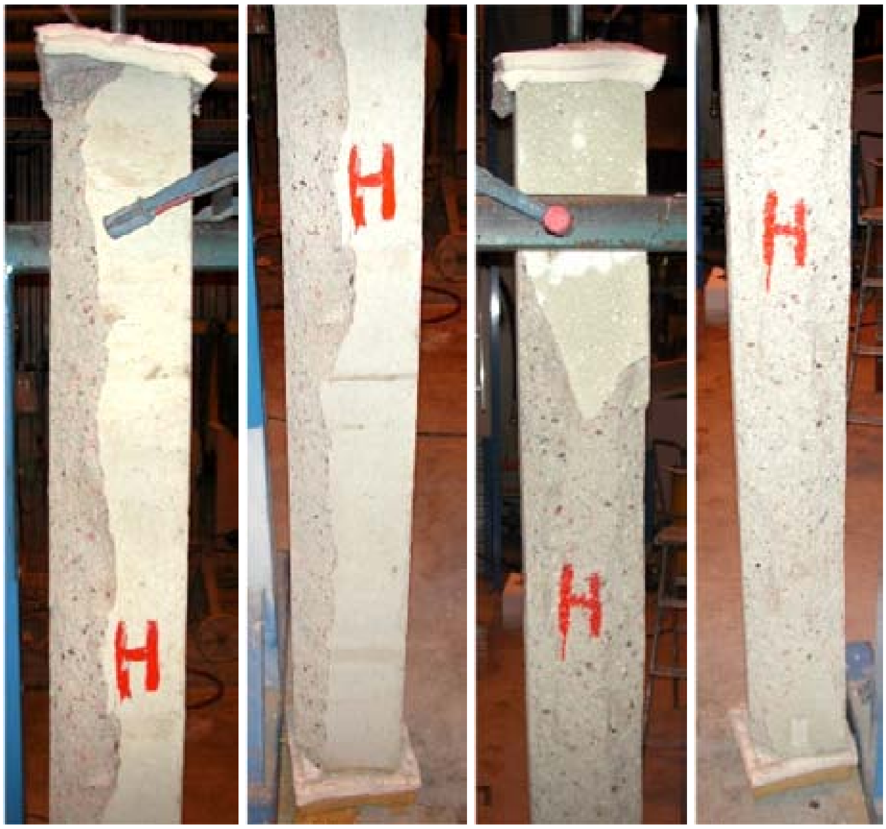

Figure B.48 Test specimen 70BK4-2.

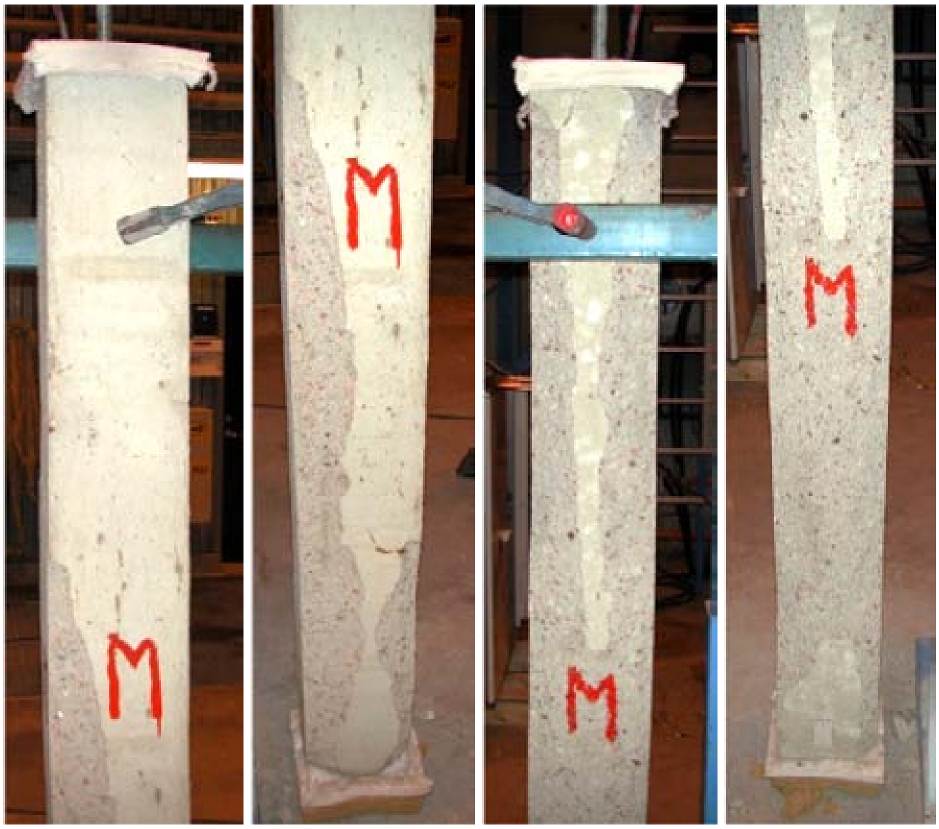

Figure B.49 Test specimen 70BK4-3.

Concrete 70BG0

Figure B.50 Test specimen 70BG0-1.

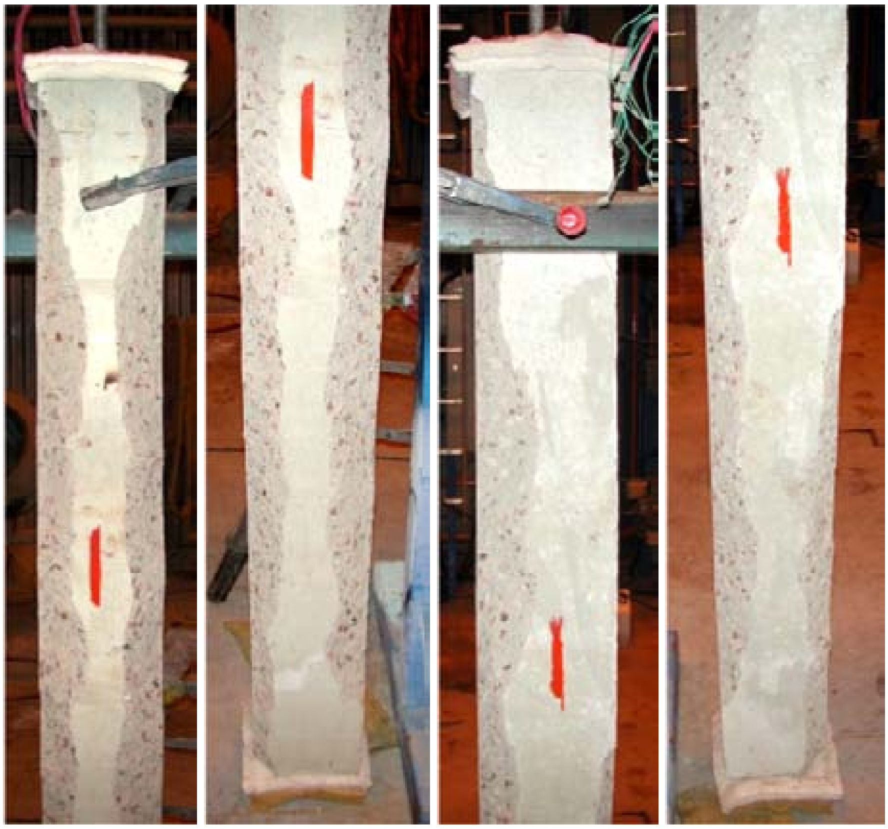

Figure B.51 Test specimen 70BG0-2.

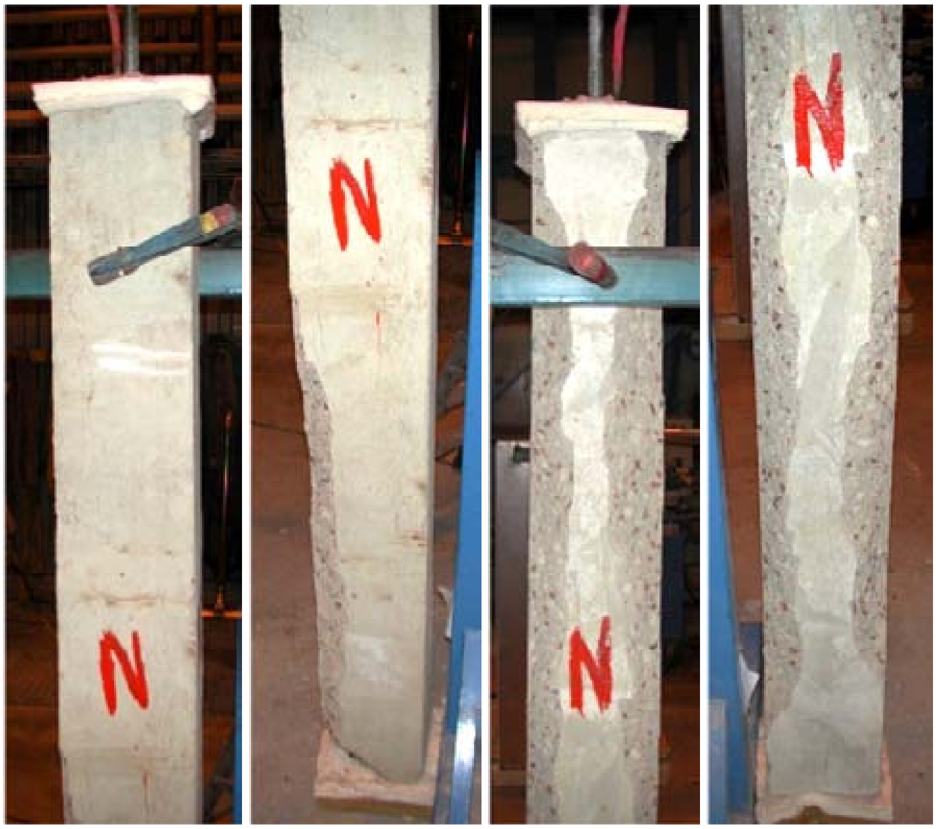

Figure B.52 Test specimen 70BG0-3.

Concrete 70BR0

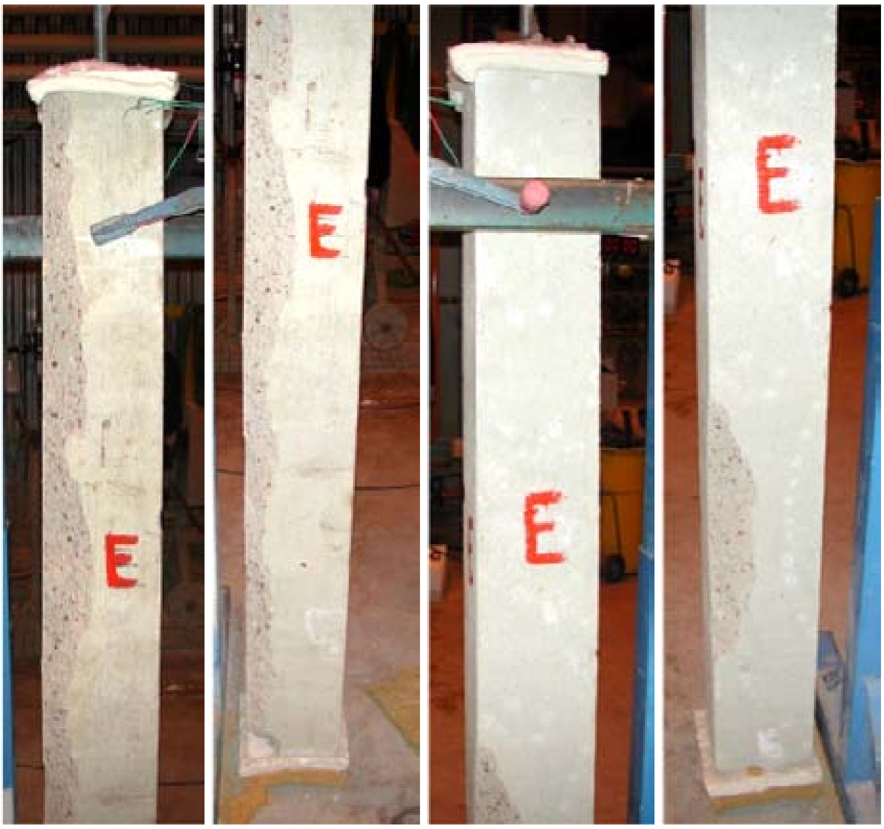

Figure B.53 Test specimen 70BR0-1.

Figure B.54 Test specimen 70BR0-2.

Lars Boström

The performance of some self compacting concretes when exposed to fire

- Appendix C -
Mix proportions of the concrete

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Appendix C - Mix proportions of the concrete

Concrete with Degerhamn Standard cement

Concrete	**40AG0**	**40AK0**	**40AK2**	**40AK4**	**40AR0**
Crushed 12-16	624	595	572	-	857
Crushed 8-11	-	-	-	326	-
Crushed 0-8	1043	1040	998	1176	758
Glass filler	62	-	-	-	-
Limestone powder	-	149	181	171	-
Cement	430	411	433	487	518
Cementa 88L	-	-	-	-	0,161
Microair				0,188	
Sikaair HPV	0,235	-	-	-	-
Sikaair 15B	-	0,130	0,132	-	-
Water	172	164	173	195	206
Glenium (wet)	-	-	-	10,67	-
Peramin F	-	-	-	-	10,4
Sikament 56	4,05	4,82	8,20	-	-
Plastic fibre	-	-	2	4	-
Flytmedel (%) ???	1,0	1,2	1,85	1,7	2,0
Prestress (kN)	112	112	112	112	112
Density (kg/m3)	2330	2360	2360	2370	2350
Air content (%)	5,0	5,1	2,5	2,8	4,0

Concrete with Skövde Bygg cement

Concrete	**40BK0**	**40BR0**	**55BK0**	**55BK2**	**55BK4**	**55BR0**
Crushed 12-16	602	1004	234	119	-	452
Crushed 8-11	-	-	362	244	316	360
Crushed 0-8	1052	742	1049	1140	1198	1029
Limestone powder	130	-	242	241	233	-
Cement	447	436	308	344	382	346
Water	179	175	170	189	210	191
Glenium (wet)	-	-	-	-	12,14	-
Peramin F	-	2,73	-	-	-	2,09
Sikament 56	9,78	-	8,16	10,14	-	-
Plastic fibre	-	-	-	2	4	-
Flytmedel (%) ???	2,2	0,6	1,5	1,75	2,0	0,57
Prestress (kN)	112	112	112	112	104	122
Density (kg/m3)	2420	2360	2380	2390	2350	2380
Air content (%)	-	-	1,3	1,1	-	1,5

Concrete	**70BG0**	**70BK0**	**70BK2**	**70BK4**	**70BR0**
Crushed 12-16	551	631	583	-	356
Crushed 8-11	-	-	-	220	351
Crushed 0-8	1166	1109	1015	1241	1088
Glass filler	79	-	-	-	-
Limestone powder	-	189	226	256	-
Cement	316	268	294	312	267
Water	222	188	207	219	195
Glenium (wet)	-	-	-	11,1	-
Sikament 56	5,30	9,41	4,89	-	-
Plastic fibre	-	-	2	4	-
Flytmedel (%) ???	1,65	3,50	1,64	2,00	-
Prestress (kN)	104	104	104	104	104
Density (kg/m3)	2340	2390	2330	2320	2250
Air content (%)	1,7	2,6	-	-	5,0

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