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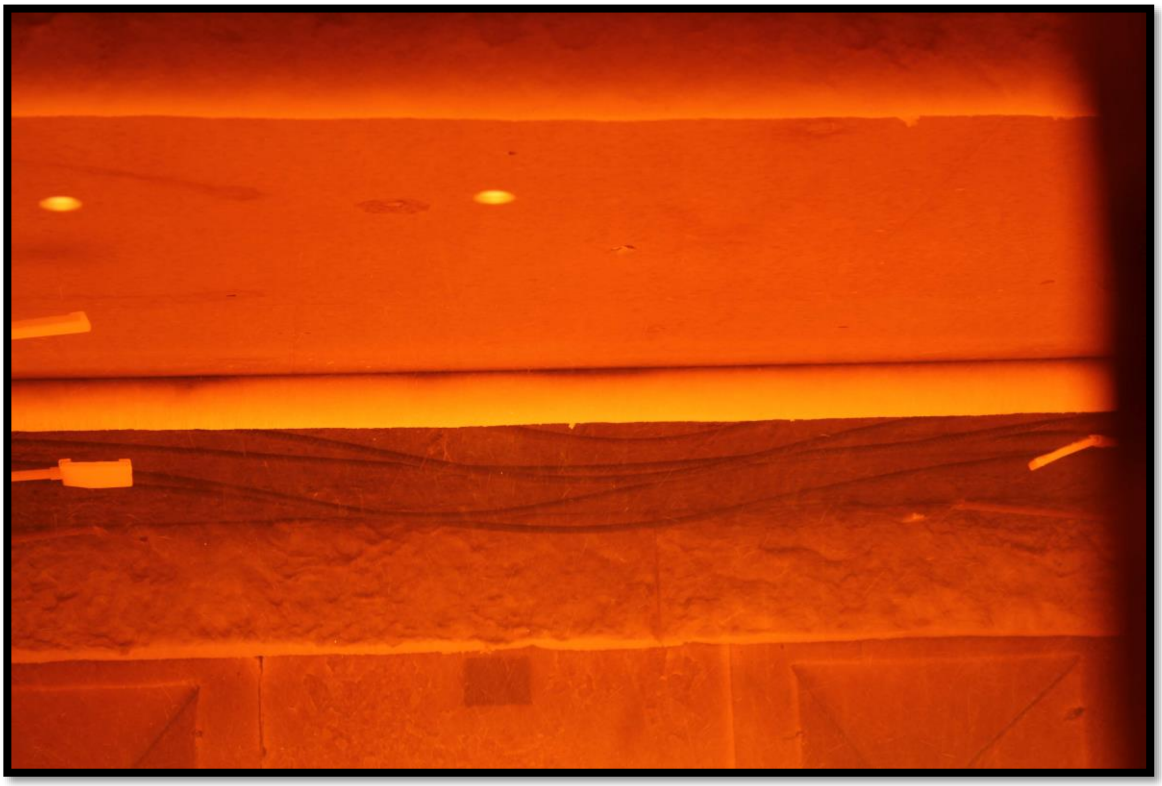

Screening test methods for determination of fire spalling of concrete

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RISE Report : 2018:05

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Abstract
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The fire resistance of concrete structures is generally good, but for some types of concrete fire spalling can reduce the fire resistance significantly. Therefore, methods are needed to predict whether a concrete will spall when exposed to fire and the severity of spalling.

The objective of the present project was to develop an intermediate scale test method for the evaluation of the spalling behavior of concrete. The test method shall be cost effective and enable screening of different concretes before a full scale approval test is performed. A number of different intermediate scale test methods have been evaluated regarding the precision to reproduce the spalling behavior of that observed in full scale tests.

Of the different test specimen shapes and methods, a circular test specimen where the concrete is casted in a steel tube has shown the best correlation to the full scale tests performed. This specimen is easy to produce, and the fire test can be performed on a small furnace.

Key words: concrete, fire spalling, fire resistance, test method

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Content

Preface

The present project is a continuation of several projects performed in the past, where many different organisations have been involved in the work as well as supporting financially. It would not have been possible to carry out this study without the knowledge build by the previous projects.

This part of the study has been financially supported by the Swedish Transport Administration and the Development Fund of the Swedish Construction Industry, SBUF, which are gratefully acknowledged.

Furthermore, voluntary work has been done by members in RILEM TC SPF of which we specially would like to thank Cracow University of Technology, Poland, University of Edinburgh, Scotland, and Gunma University, Japan, who have all performed extra tests included in the study.

We would also like to thank the personnel at RISE Safety, Fire Resistance, who have helped with manufacturing, valuable discussions and ideas and performing the numerous tests.

Borås, March 2018
Lars Boström, Robert McNamee, Joakim Albrektsson and Pär Johansson

Summary

Presently there is no prescribed method for screening tests of the spalling behaviour of concrete exposed to fire. There are some frequently used screening methods, but these have the drawback that the correlation to the behaviour of a large scale test is rather bad. In the present project a number of alternate test set-ups and specimen geometries have been examined and compared to results obtained in full scale testing in order to develop a screening test that is cost effective and have a good correlation to a large scale test.

Several different methods have been studied, some that are currently used in other countries, and some that are used in Sweden but that have been further developed and improved. A total of seven different intermediate scale test methods have been studied and compared to full scale tests. The main parameter examined is the correlation between the spalling behaviour obtained in the intermediate and the large scale tests. In addition has also the other aspects been evaluated regarding the production and costs for the intermediate test samples, and whether and special requirements are needed for the intermediate tests.

The results from this study show that a circular test specimen, with a diameter of 600 mm and height 300 mm, where the concrete is casted in a steel tube with a wall thickness of 10 mm gives the best correlation to the large scale tests. This specimen has also other advantages such as it is very easy and cheap to manufacture, and it can be tested on a small furnace which makes the test simple and fast to carry out.

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 fully known. There are several problems which are still not sufficiently recognized and investigated. The present study is focused on how the fire spalling behaviour of concrete can be assessed through small or medium size testing.

There are several causes that may lead to damage of concrete when exposed to fire. In the present study only spalling will be considered.

Concrete is a family name of materials where aggregates are bonded with cement. Here is thus a large amount of different concretes with completely different behaviour. For instance, the difference between conventional vibrated concrete and self-compacting concrete is in many cases the use of fine filler. The filler could be glass or limestone powder. By adding filler, the concrete will be much denser and thus the permeability will be lower. Also, the absence of vibration during manufacturing makes the transition zones around the aggregates denser. 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 Boström, Jansson (2008) and, Jansson, Boström (2008) and Jansson, Boström (2013).

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 (2004). It was shown that the geometry of the test specimen and the load level and configuration have a significant effect on the spalling. This is exemplified by test results were loaded medium and full scale tests have resulted in severe spalling while unloaded small scale tests have not spalled.

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 vague. 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 EN 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.

Since many types of concrete may spall severely when exposed to fire it is today a common practice to add a small amount of polypropylene fibres in the concrete mix, usually between 0.5-2.0 kg per m^3 concrete. This addition of fibres prevent fire spalling, but it is important than enough fibres are added. Since these fibres may introduce problems such as increase of air in the concrete and reduced workability, an optimization of the fibre content is often necessary. At present the only option to determine whether the spalling behaviour of concrete is good enough is by testing. Therefore, a small or intermediate size test method is needed since the standardized large size methods are very time consuming and expensive to carry out.

Testing of concrete can be done on many different scales, and they have different objectives. Figure 1 show three scales of tests used for examining spalling of concrete, material screening tests, intermediate scale tests and product screening test.

A typical material screening test is when a cube or cylinder, with a size like the specimens used for determining the strength of concrete, is exposed to high temperature. The link between this scale of test and the behaviour of a final product such as a concrete wall is very weak regarding the spalling behaviour.

An intermediate scale test has a much better correlation to a large scale test, and is thus a good tool for screening different concrete mixes before performing a full scale test.

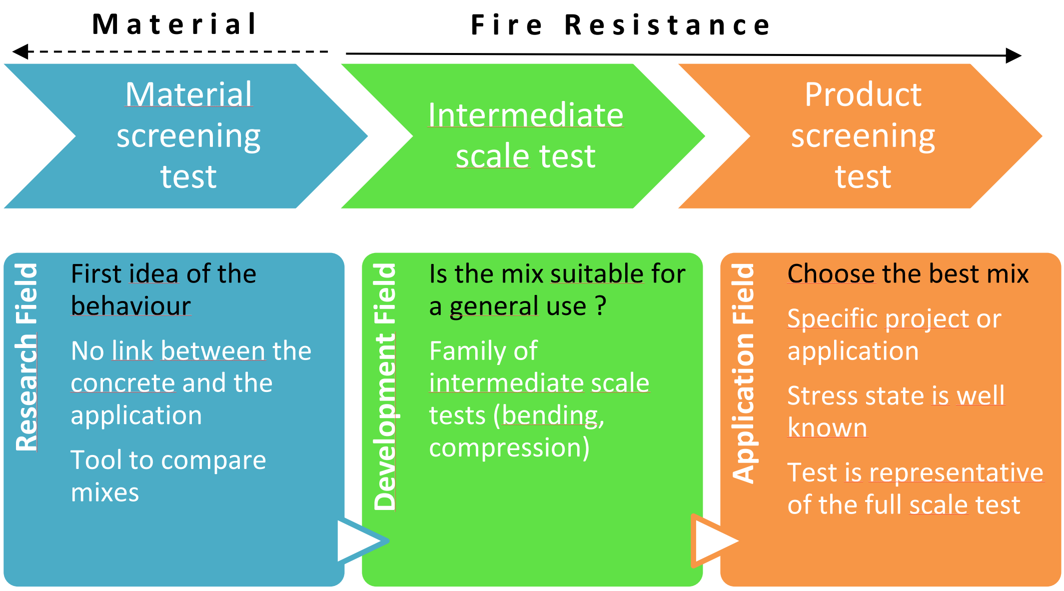

Figure 1. Schematic view on different scale of tests and their applicability[1].

[1] Based on discussions in RILEM TC SPC 256 Spalling of concrete due to fire: testing and modelling.

1.2 Objectives

The project had the following objectives;

1. To experimentally examine a number of different small and medium size test methods
2. Make some large scale reference test for validation of the examined small and medium size methods
3. To propose a small or medium size test method for screening tests of the spalling behaviour of concrete exposed to fire.

The aim of the project is thus to define a small or medium size test specimen with which the risk for fire spalling can be screened for different concretes. This is of value for the industry when making decisions on which concrete mixes that may have good enough behaviour to pass an eventual large scale test.

1.3 Limitations

A very limited number of concretes have been examined. This was decided in order to examine many different test methods within the limits of the project.

In the large scale tests have only slab specimens been tested, i.e. only one sided fire exposure.

1.4 Research team and reference group

Robert Jansson McNamee, presently at Brandskyddslaget and formerly at RISE Safety, has been the project leader for the first part of the project and then when moving to Brandskyddslaget continued as a research team member when Lars Boström stepped in as the project leader. The main research work on the fire tests has been carried out by Robert Jansson McNamee, Pär Johansson, Joakim Albrektsson and Lars Boström from Brandskyddslaget and RISE Safety. The practical work with testing has been carried out by Bengt Bogren, Patrik Nilsson, Martin Rylander, Peter Lindqvist, Fredrik Kahl and Kent Pettersson from RISE Safety.

A reference group with the following participants was coupled to the project:

Staffan Carlström, Swerock
Benhnam Dalili, Trafikverket
Arvid Hejll, Trafikverket
Hans Hedlund, Skanska
Joakim Jepsson, Skanska
Alf Nilsson, Trafikverket
Ulf Lundström, Trafikverket

Ingemar Löfgren, Thomas Conrete Group
Henrik Modig, Trafikverket
Ken Ryberg, Trafikverket
Iad Saleh, NCC
Johan Silfwerbrand, KTH
Jan Trädgårdh, CBI
Kjell Wallin, Projektengagemang
Mikael Westerholm, Cementa

In the reference group the following participants were included in a steering group who was invited to discuss the second half of the project when the first half of the project was finished:

Hans Hedlund, Skanska Sverige AB
Ingemar Löfgren, Thomas Concrete Group AB
Alf Nilsson, Trafikverket
Mikael Westerholm, Cementa
Johan Silfwerbrand, KTH

2 Materials

The experimental campaign was divided in two test series each including three different concrete mixes. The aim with the present choice of concrete mixes was to ensure that the concretes would represent one that would not spall, one with severe spalling, and one that spalls to some extent.

The first series included two mixes with water/cement ratio (w/c) 0.33, one with polypropylene fibre addition and a second without fibre addition and a third mix with w/c 0.40 without fibres. The fibres used in the study was SIKA Crackstop with a length 6 mm and diameter 18 µm. The w/c 0.4 mix represents a typical Swedish tunnel concrete. In the second test series three different amounts of fibres, 0, 0.2 and 1 kg/m^3, were added to the same w/c 0.40 mix as used in the first test series. This makes Series 1, Mix 3, and Series 2, Mix 4, identical but moulded at separate times. All mixes can be seen in Table 1.

Table 1. Concrete mixes used in the experiments.

	Cement, CEM I 42,5 N SR3 MH/LA [kg/m^3]	Water [kg/m^3]	Aggregate 0-8 mm [kg/m^3]	Aggregate 8-16 mm [kg/m^3]	PP fibres 18 µm [kg/m^3]
Series 1, Mix 1 w/c 0.33, 1 kg PP	510	168	796	855	1.0
Series 1, Mix 2 w/c 0.33	510	168	796	855	-
Series 1, Mix 3* w/c 0.4	430	168	866	860	-
Series 2, Mix 4* w/c 0.4	430	168	866	860	-
Series 2, Mix 5 w/c 0.4, 0.2 kg PP	430	168	866	860	0.2
Series 2, Mix 6 w/c 0.4, 1 kg PP	430	168	866	860	1.0

** Series 1, Mix 3, and Series 2, Mix 4 is identical but moulded at separate times.*

During moulding the pre-mixed concrete were delivered from Thomas Betong in Borås and the moulding was performed in the fire resistance hall of RISE Fire Research.

Material characteristics measured during moulding and compressive strength of the different mixes are summarized in Table 2. The reason for the large deviation between the identical mixes (Series 1, Mix 3 and Series 2, Mix 4) are not known but there is a difference in test method as the compressive strength tests in series 1 were performed on 100 x 100 x 100 mm^3 cubes and tests in series 2 were done on drilled cores from larger slabs, but this difference in test method give in theory a difference in the other direction. After moulding all specimens were stored in plastic in indoors climate until approximately a week before the tests when the plastics were removed.

Table 2. Moulding date, material characteristics and compressive strength.

Mix	Moulding date	Air content [%]	Flowability [mm]	Compressive strength, 28 days [MPa]	Compressive strength, 3 months [MPa]
Series 1, Mix 1 w/c 0.33, 1 kg PP	2016-09-06	7.4	220	53	61**
Series 1, Mix 2 w/c 0.33	2016-09-12	2.7	270	70	79**
Series 1, Mix 3* w/c 0.4	2016-09-12	7.8	180	42	51**
Series 2, Mix 4* w/c 0.4	2017-04-03				70***
Series 2, Mix 5 w/c 0.4, 0.1 kg PP	2017-04-12				62***
Series 2, Mix 6 w/c 0.4, 1 kg PP	2017-04-20				68***

** Series 1, Mix 3, and Series 2, Mix 4 is identical but moulded at separate times.*
***Compressive strength measured on 100 x 100 x 100 mm^3 cubes. Average value from three specimens.*
****Compressive strength measured on drilled cores from large slabs. Average value from three specimens.*

In order to measure the moisture content of the concrete at the time of the fire tests, special specimens were manufactured for this purpose. Concrete was cast in PVC pipes with diameter 100 mm and with the same length as the large specimens in the test series (600 mm in series 1 and 300 mm in series 2). The PVC pipes were then stored parallel to the large slabs (both in plastics) and moisture content were determined at about the same date as the fire testing. It might seem a little strange to use the pipes when the storage of all specimens was in plastic, but this was done to test the methodology. The moisture content at different depths, 0-50 mm and 50-100mm, was determined by cutting a notch and split the cylinder before drying in 105°C. The measured moisture contents are shown in Table 3. The reason for the large deviation between the identical mixes (Series 1, Mix 3 and Series 2, Mix 4) are not known but as seen in Table 2, mix 4 had a much higher strength so in practice there were a difference between the mixes. Also, apparent when analysing the results are that the area closest to the surface is drier, whether this is caused by diffusion (drying) through the plastic or different cement aggregate ratios in different zones are not known.

Table 3. Moisture content at different depths.

	Moisture content 0-50 mm from surface [%]	Moisture content 50-100 mm from surface [%]
Series 1, Mix 1 w/c 0.33, 1 kg PP	4.3	5.0
Series 1, Mix 2 w/c 0.33	5.3	5.8
Series 1, Mix 3* w/c 0.4	4.9	5.4
Series 2, Mix 4* w/c 0.4	3.8	4.5
Series 2, Mix 5 w/c 0.4, 0.1 kg PP	4.5	5.2
Series 2, Mix 6 w/c 0.4, 1 kg PP	4.8	5.1

** Series 1, Mix 3, and Series 2, Mix 4 is identical but moulded at separate times.*

3 Specimens

3.1 Specimens in series 1

3.1.1 Large scale slabs, series 1

The dimensions of the large slabs were (width x length x thickness) 1670 x 4000 x 600 mm^3. The test specimens had the same thickness and reinforcement as roof slabs in the "Norra länken" tunnel built in Stockholm, Sweden. The concrete cover on the lower fire exposed side was 50 mm and the reinforcement included 16 mm bars with centre distance 25 cm along the slab and 25 mm bars with centre distance 12.5 cm across the slabs. On the upper side of the slabs the concrete cover was 60 mm with 16 mm bars along the slabs and 25 mm bars across the slab, both types spread out with a centre distance of 25 cm. Each slab was equipped with 12 thermocouples. The thermocouples were placed in five measurement stations, one in the centre of the slab and one in the centre of each quarter of the slab. Each station had one thermocouple on the 16 mm bars and one thermocouple on the 25 mm bar. At the centre position two extra thermocouples was mounted at the surface. The TC placement on the reinforcement bars are illustrated in Figure 2.

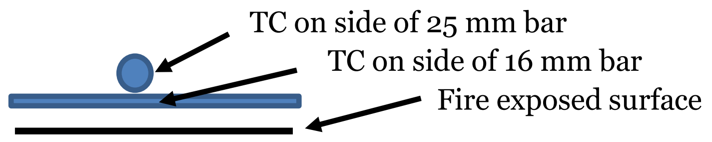

Figure 2. Placement of thermocouples on reinforcement bars.

3.1.2 Small slabs, series 1

The dimensions of the small slabs were (width x length x thickness) 600 x 500 x 400 mm^3. Three layers of reinforcement nets were used at the depths 30, 60 and 90 mm. The spacing in the net was 100 x 100 mm^2 and the bar diameter 8 mm. A thermocouple was attached on the reinforcement net at the depth 30 mm.

3.1.3 Wedge slabs, series 1

Tapered cross section slabs were manufactured with dimension (height x width x base thickness x edge thickness) 1000 x 500 x 300 x 50 mm, see Figure 3. Centrally in the specimen, a reinforcement net was placed with a spacing of 100 x 100 mm^2 and bar diameter 8 mm. A thermocouple was attached on the reinforcement net 400 mm from the lower edge of the specimen. One of the wedge slabs had two thermocouples on each of the reinforcement bars 200, 400, 600 and 800 mm from the lower edge of the specimen.

Figure 3. Wedged slab.

3.1.4 Specimens sent to other laboratories, series 1

Additional specimens for tests outside RISE were moulded in test series 1. The specimens and results from these tests was presented at the fire spalling workshop arranged by RILEM in Borås 2017 (Jansson McNamee et al., 2017). A description of this specimens can be seen in Table 4.

Table 4. Test specimens sent to other laboratories

Description	Tested at	Geometry	Thermocouples (TC)
Small ring specimens	Gunma University, Japan	Moulded in steel rings, an inner dimeter of 300 mm, height 2 x 50 mm, steel thickness 11 mm, see Figure 4.	At exposed surface
Unreinforced loaded slabs	Edinburgh University, Scotland	0.5 x 0.5 x 0.25 m^3	Two at the surface and at the depths 20 and 60 mm.
Unreinforced slabs	Cracow University, Poland	1.2 x 1 x 0.3 m^3	Two at the surface and at the depths 20 and 60 mm.

Figure 4. Concrete moulded in steel pipes, Gunma University type.

3.2 Specimens in series 2

3.2.1 Large slabs, series 2

The dimensions of the large slabs were (width x length x thickness) 1200 x 3100 x 300 mm^3. Reinforcement net with dimension 12 mm bars with 150 mm distances was mounted 50 mm from the upper and lower sides of the slabs.

3.2.2 Small slabs, series 2

The dimensions of the slabs were (width x length x thickness) 600 x 500 x 300 mm^3. Reinforcement net with dimension 12 mm bars with 150 mm distances was mounted 50 mm from the upper and lower sides of the slabs.

3.2.3 Medium size ring specimens moulded in steel pipes, series 2

Concrete moulded in steel pipes, (outer diameter x height) 610 x 300 mm^2. The thickness of the steel in the pipes was 12.5 mm. Reinforcement net with dimension 12 mm bars with 150 mm distances was mounted 50 mm from the upper and lower sides of the slabs.

4 Test methods

4.1 Test methods in series 1

4.1.1 Large slabs, series 1

The concrete slabs were tested in a horizontal position on RISEs horizontal furnace with fire exposure from below on the same side as the bottom side during casting. Three slabs were tested at the same time. During the test the specimen were exposed to the hydrocarbon fire curve, EN 1363-2. A drawing of the test setup including placement of plate thermometers for regulating the fire exposure can be seen in Figure 5.

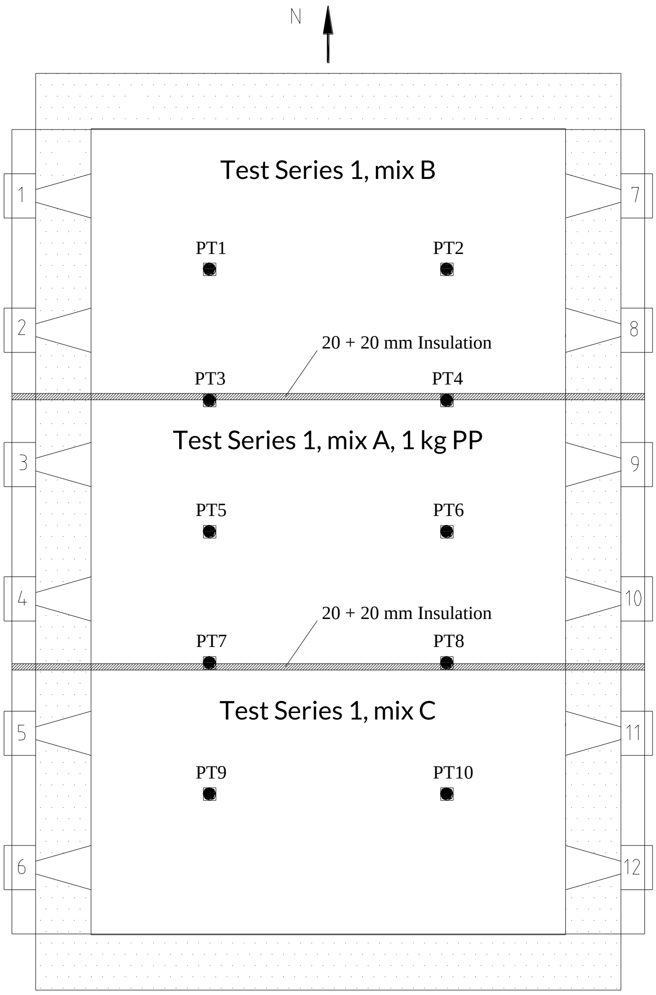

Figure 5. Large slabs, 4000 x 1670 x 600 mm3, tested on top of the horizontal furnace at RISE in test series 1. "PT" is the position of the plate thermometers inside the furnace.

4.1.2 Small slabs, unrestrained, series 1

The concrete slabs were tested in a horizontal position with fire exposure from below towards the same side as the bottom side during casting. During the test the specimen were exposed to the standard fire curve according to SP Fire 119. The temperature in the furnace was measured with a shielded thermocouple. Sketches of the test setup can be seen in Figure 6.

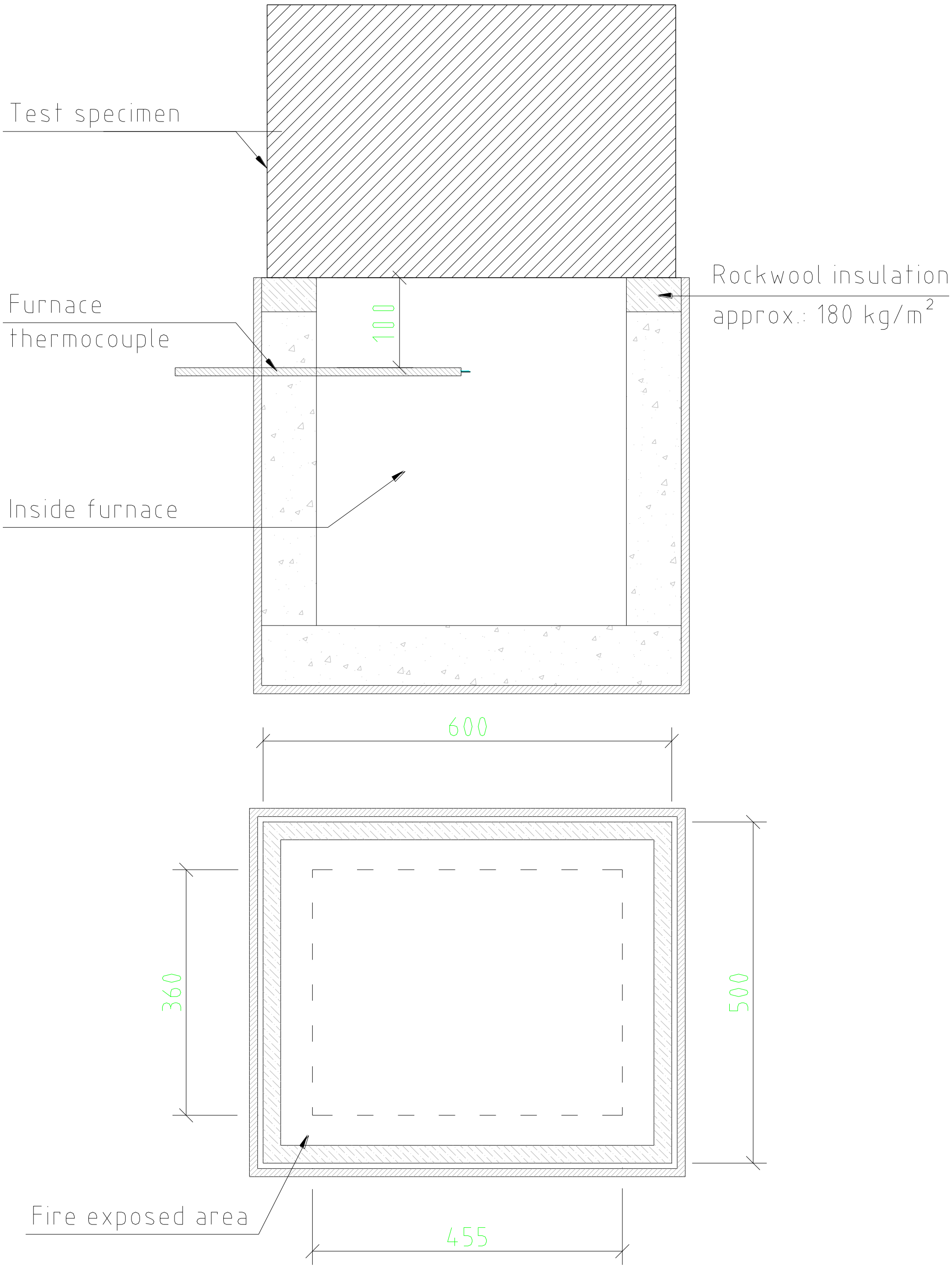

Figure 6. Small unrestrained slabs tested on a small furnace in series 1.

4.1.3 Small slabs, restrained, series 1

The concrete slabs were tested in a horizontal position with fire exposure from below towards the same side as the bottom side during casting. The test slabs were restrained by a restraining frame around the specimen during the test. The frame was built with IPE 200 profiles and to ensure a good contact between specimen and frame expandable mortar was injected in a 3 cm wide void between the specimen and the frame one day before each fire test. During the test the specimen were exposed to the standard fire curve according to SP Fire 119. The temperature in the furnace was measured with a shielded thermocouple. Sketches of the test setup can be seen in Figure 7.

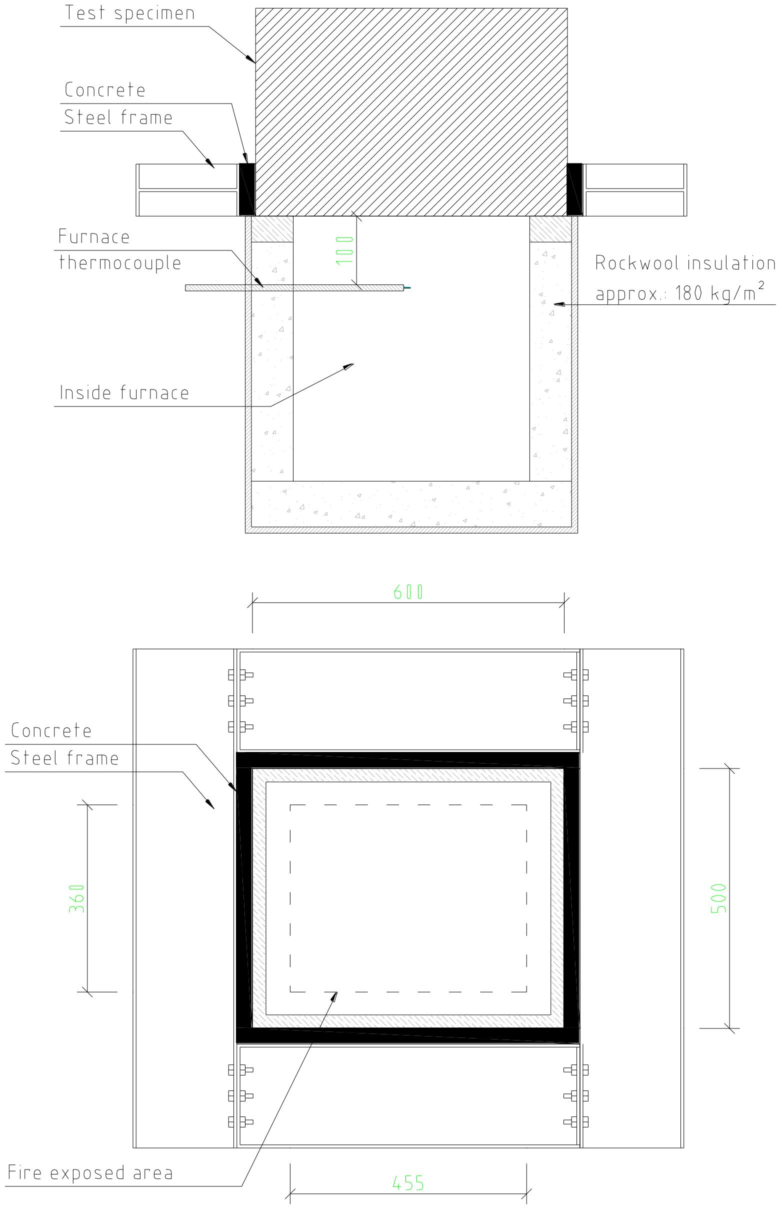

Figure 7. Small restrained slabs tested on a small furnace in series 1.

4.1.4 Wedge slabs, series 1

The wedged concrete slabs were hung from the roof of RISEs horizontal furnace in groups of three. Only the two large sides faced the heat in the furnace. The edges of the wedges were covered with insulation. During the test the specimen were exposed to the standard fire curve, EN 1363-1. Sketches of the test setup including positions of the plate thermometers can be seen in Figures 8 - 9.

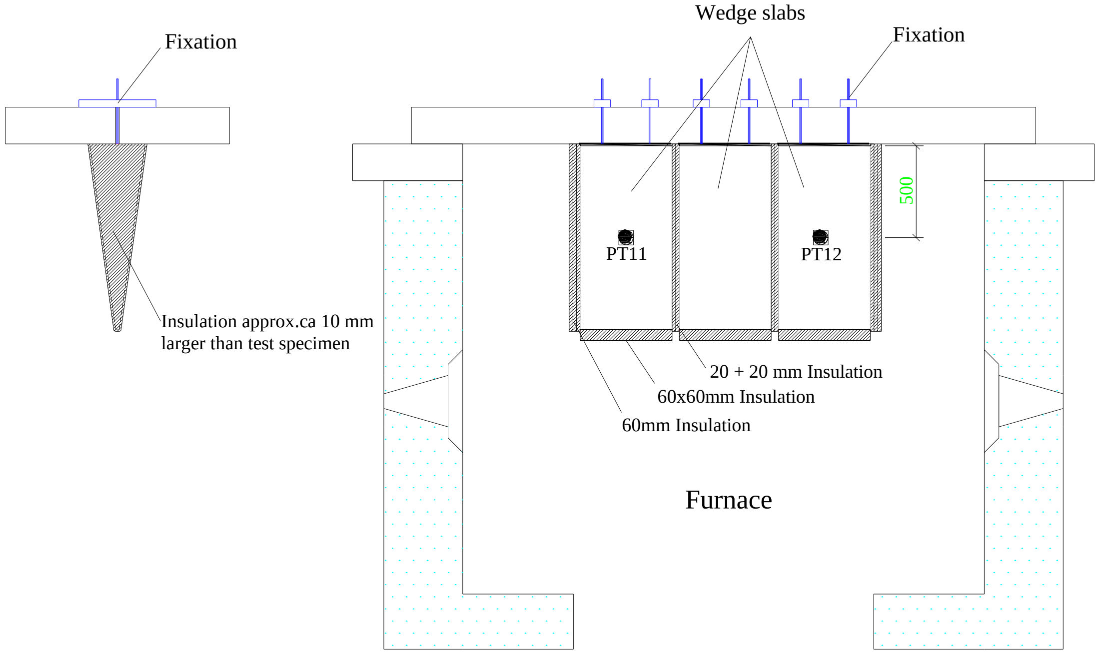

Figure 8. Wedged slabs hanging from the roof of the horizontal furnace in test series 1. "PT" is the position of plate thermometers to control the temperature in the furnace.

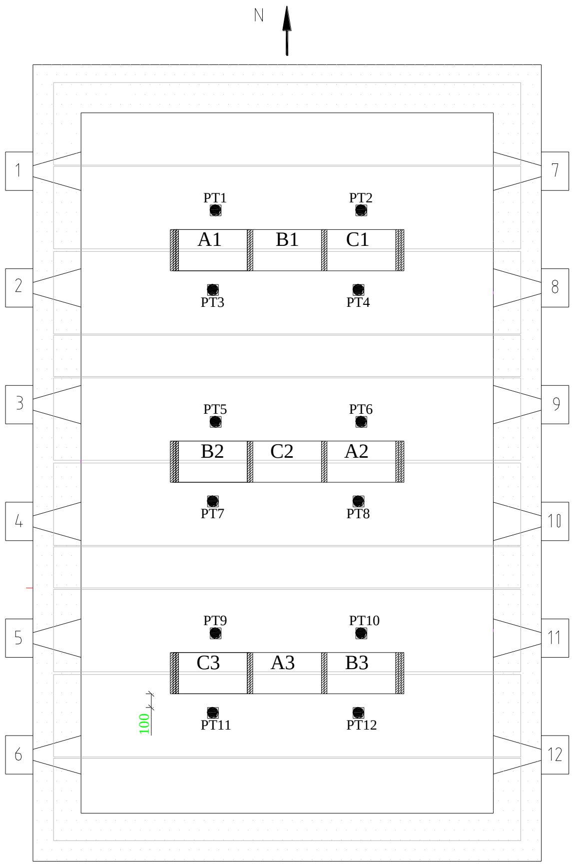

Figure 9. The position of the wedge slabs. The slabs are hanging from the roof of the horizontal furnace in test series 1. "PT" is the position of plate thermometers to control the temperature in the furnace.

4.1.5 Specimens sent to other laboratories in series 1

The tests of small ring specimens at Gunma University, Japan, were performed on a small gas fuelled furnace. Standard fire exposure measured with a shielded thermocouple was used during the tests.

During the tests performed at The University of Edinburgh the H-TRIS setup was used, described by Scotland, Maluk et al. (2016). This test method works by directly controlling the incident radiant heat flux that samples are subjected to during testing. The incident heat flux – time thermal exposure used was calibrated to correspond to the thermal exposure experienced by samples previously tested to an EN 1363-1 temperature time curve using the Promethee furnace at CERIB, France, Richard (2015). During the tests, the specimens were loaded with a uniaxial compression of 5 MPa. This load level was maintained throughout testing. All tests were stopped after the first occurrence of spalling. The test setup is shown in Figure 10.

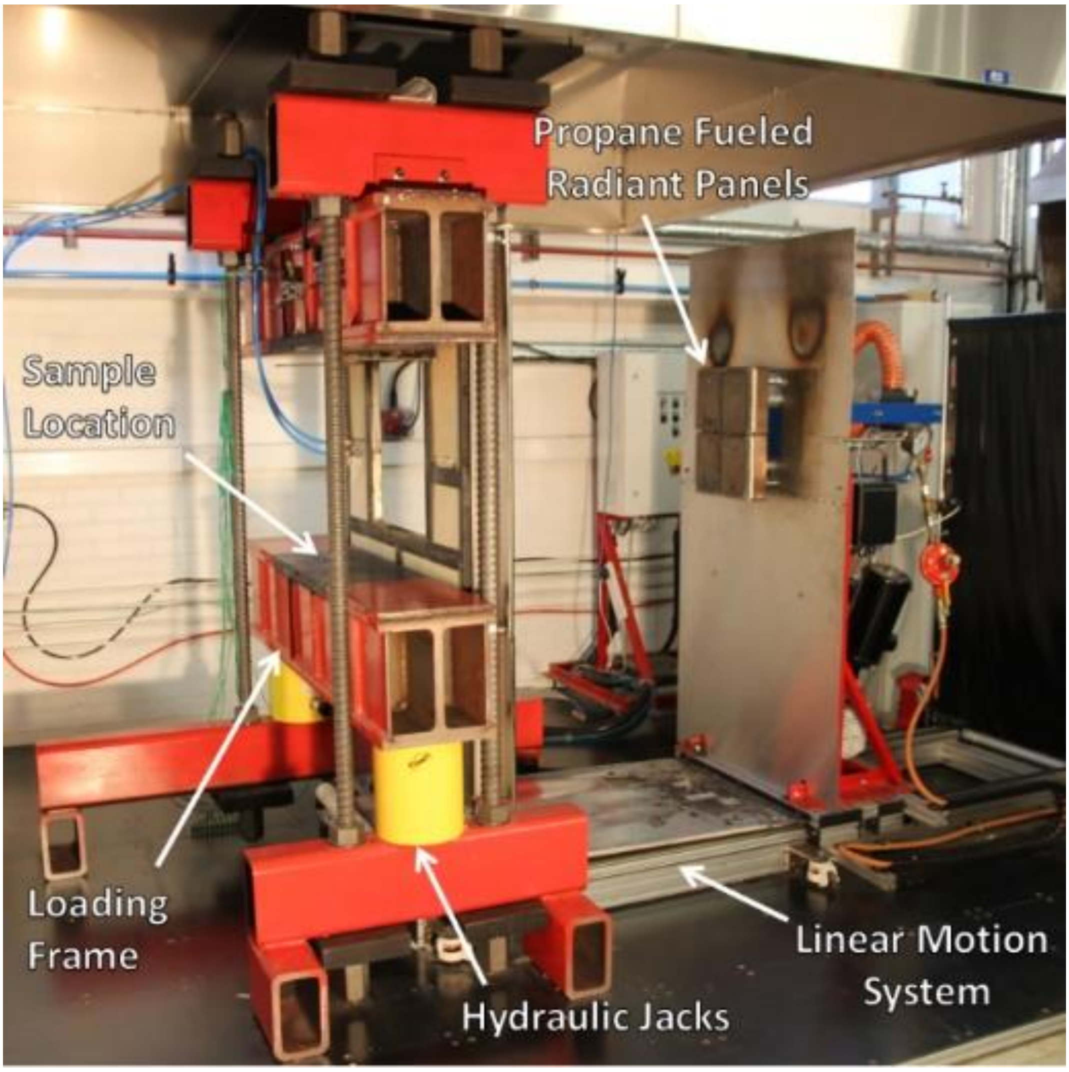

Figure 10. H-TRIS Test apparatus at the University of Edinburgh used in test series 1.

The tests at the University of Cracow, Poland was performed on top of the “Dragon” furnace, Hager et al. (2014), The slabs were freely supported by thermally insulated external walls of the furnace that were 0.125 m in thickness. As a result, the fire exposed surface area was 0.95 x 0.75 m^2. Standard fire exposure measured with a shielded thermocouple was used during the tests. The Dragon furnace can be seen in Figure 11.

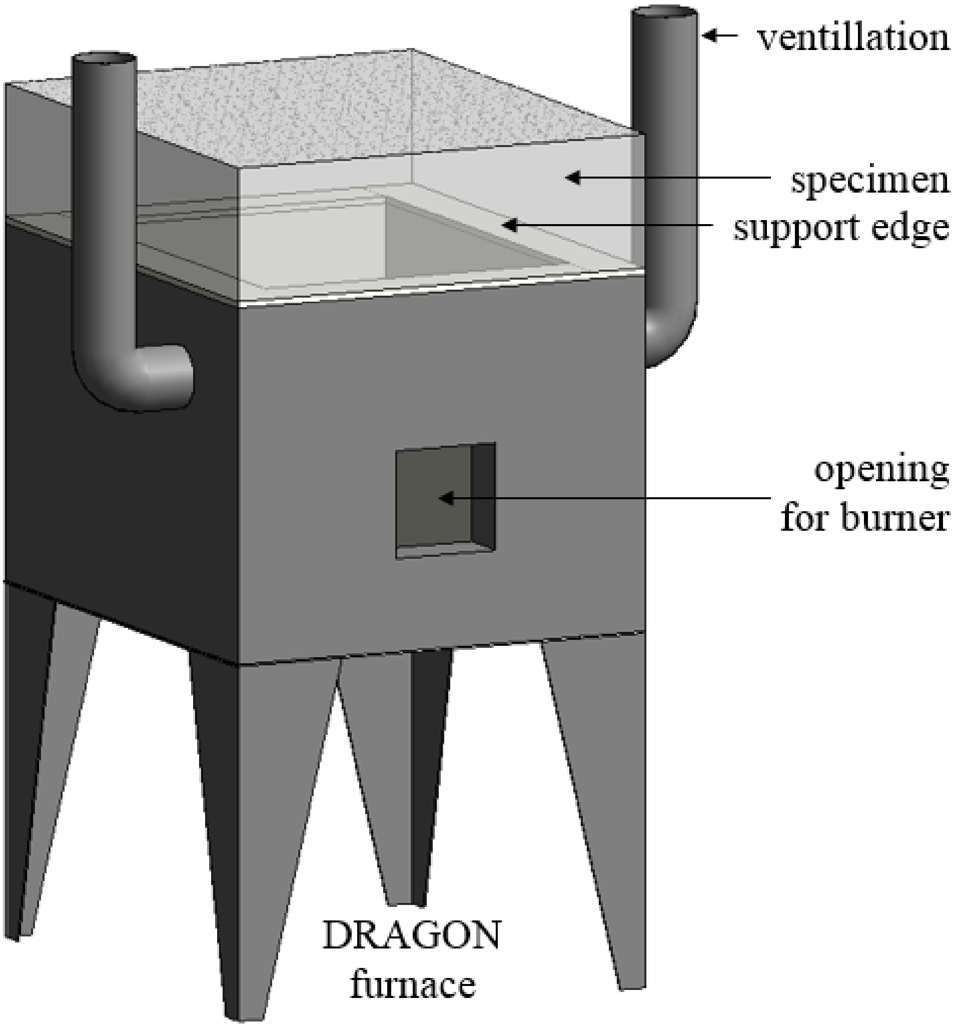

Figure 11. "Dragon" furnace used at the University of Cracow, Poland, in test series 1.

4.2 Test methods in series 2

4.2.1 Large slabs, series 2

The concrete slab was tested in a standing vertical position in front of RISEs vertical furnace with fire exposure on the same side as the bottom side during casting. Steel plates with dimension (width x length x thickness) 100 x 1200 x 10 mm^3 was mounted on the upper and lower edges of the slab nearest the fire exposed plane. During the test the specimen was exposed to the standard fire curve, EN 1363-1.

The test specimen with the steel plates was placed with the steel plates centrically below the steel beam.

The test specimen was loaded with a hydraulic loading system from above. The load was transferred into the test specimen through a steel beam. The total load level was 808 kN.

Sketches of the test setup can be seen in Figures 12 - 13.

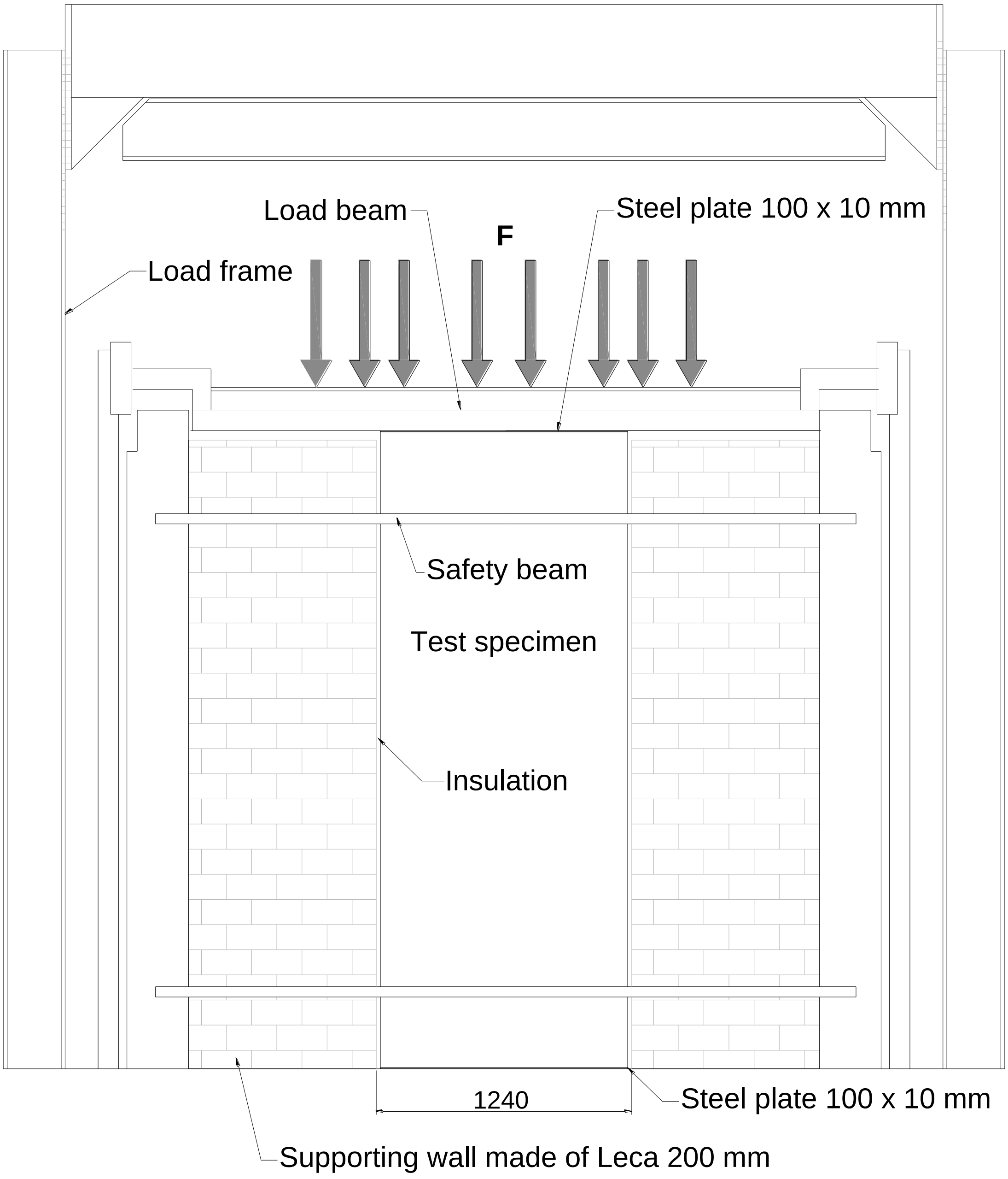

Figure 12. Large slabs tested at the vertical furnace in the series 2. Test setup as seen from the not fire exposed side.

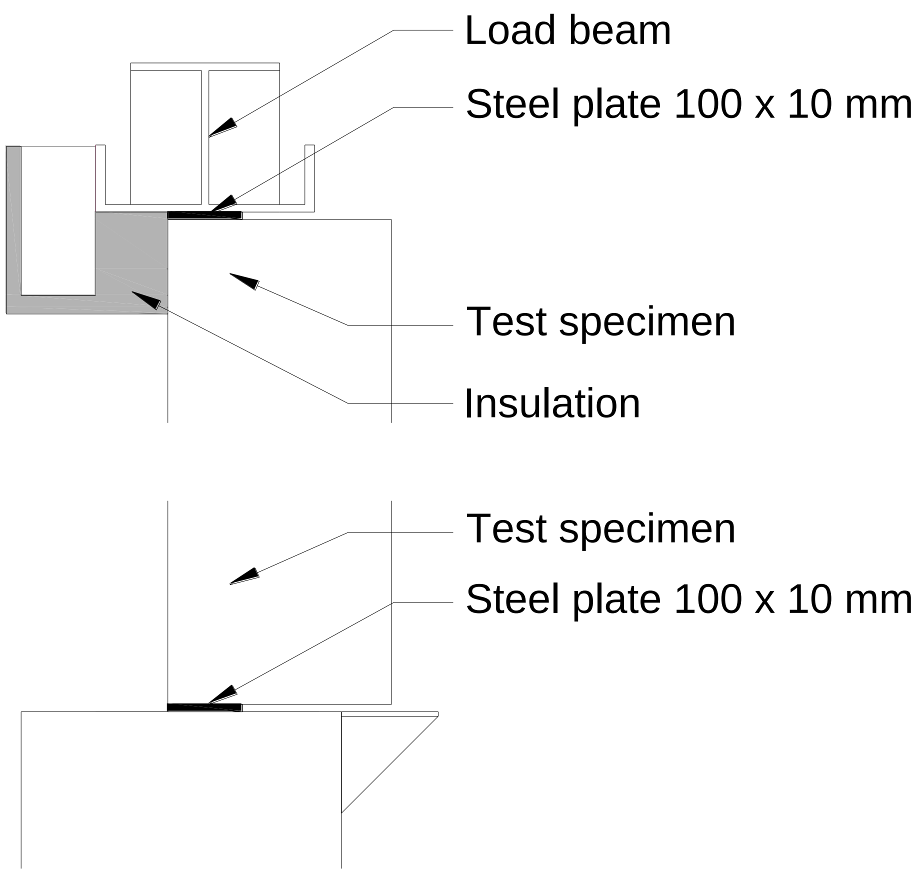

Figure 13. Details of the supports during the tests at the vertical furnace in series 2.

4.2.2 Small slabs, restrained, series 2

The concrete slabs were tested in a horizontal position with fire exposure from below towards the same side as the bottom side during casting. The test slabs were restrained by a restraining frame around the specimen during the test. The frame was built with IPE 200 profiles and to ensure a good contact between specimen and frame expandable mortar was injected in a 3 cm wide void between the specimen and the frame one day before each fire test. During the test the specimen were exposed to the standard fire curve. This test setup is identical with the restrained tests of small slabs in test series 1 except for the height and steel reinforcement in the specimens. The height of the specimens was 300 mm in this tests and 400 mm in the tests in series 1. Sketches of the test setup can be seen in Figure 14.

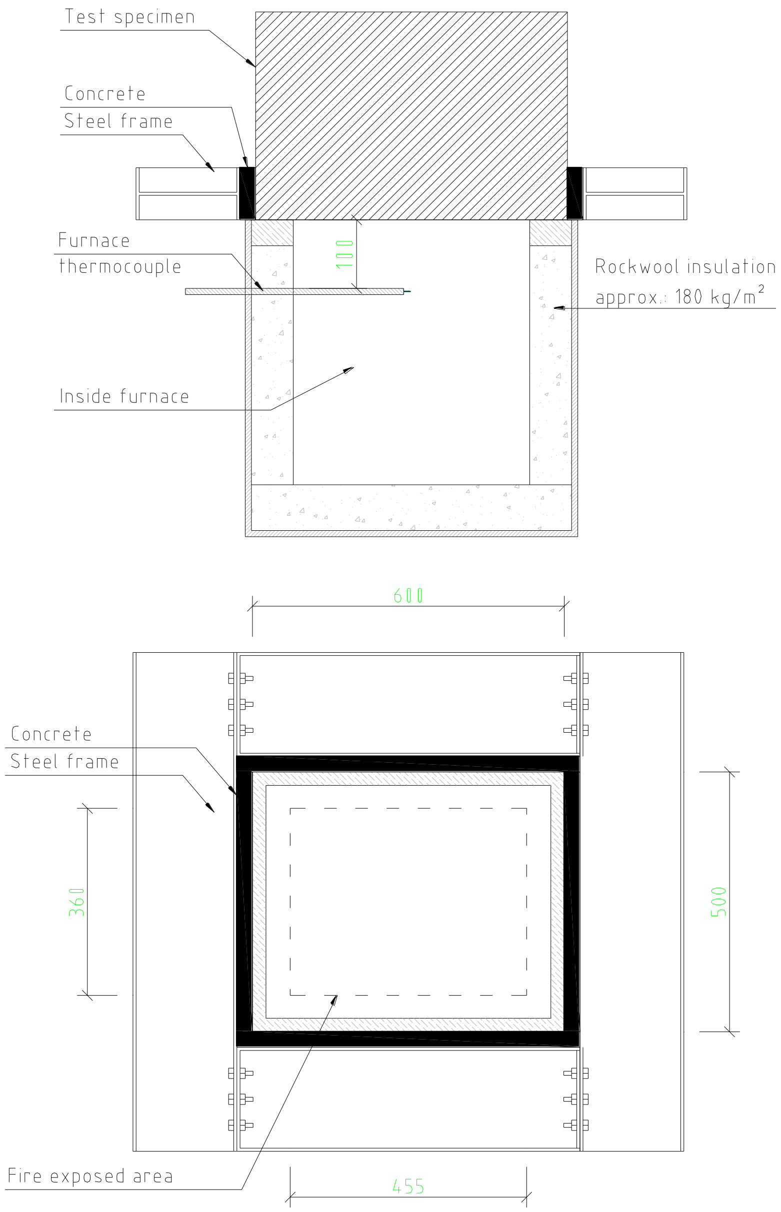

Figure 14. Small restrained slabs tested on a small furnace in test series 2 (identical test frame as in restrained tests in test series 1).

4.2.3 Medium size ring specimens, series 2

The concrete slabs were tested in a horizontal position with fire exposure from below towards the same side as the bottom side during casting. During the test the specimen were exposed to the standard fire curve according to SP Fire 119. The temperature in the furnace was measured with a shielded thermocouple.

Sketches of the test setup can be seen in the Figure 15.

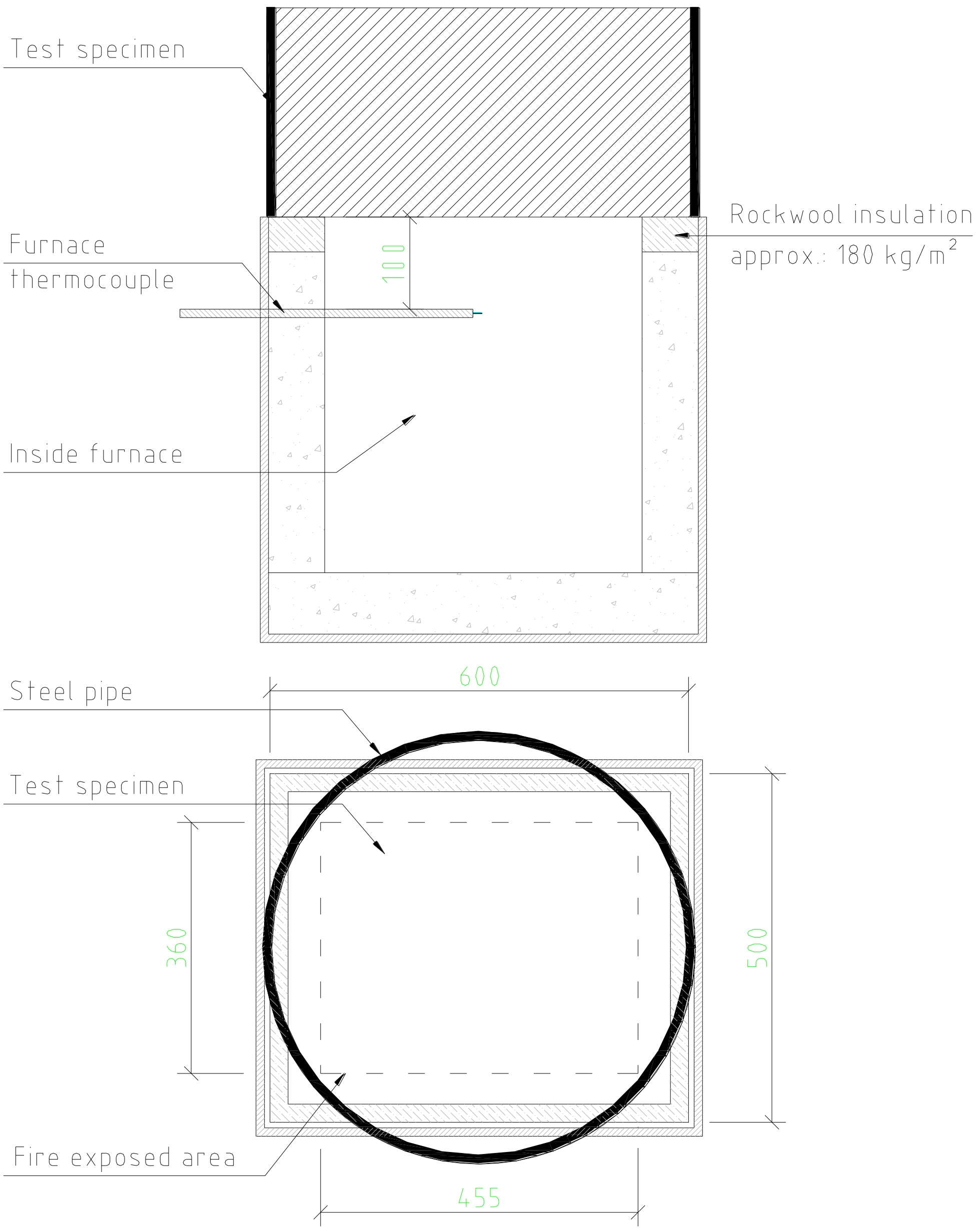

Figure 15. Test setup for medium size ring specimens in series 2.

4.3 Test matrix

A summary of the whole test program can be seen in Table 5.

Table 5. Test matrix.

Test method	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Series no 1						
Large slabs, horizontal, unloaded test	1	1	1			
Small slabs (unrestrained)	3	3	3			
Small slabs (restrained)	3	3	3			
Wedge Slabs	3	3	3			
Small ring specimens, Gunma University type	2	2	2			
Unreinforced loaded slabs, Edinburgh University type			3			
Unreinforced slabs, Cracow University type			2			
Series no 2						
Large slabs, vertical, loaded test				1	1	1
Small slabs (restrained)				2	2	2
Medium size ring specimens				3	3	3

5 Results and discussion

In this chapter the results will be summarized in a series of diagrams, complete results including temperature measurements and observations can be found in the Appendix. The main characteristics of the mixes and spalling results are summarized in Table 6.

Table 6. Measurements of maximum spalling depths (in mm if nothing else is noted).

Test method	Mix 1 w/c 0.33 1kg/m^{3}PP	Mix 2 w/c 0.33 0kg/m^{3}PP	Mix 3 w/c 0.40 0kg/m^{3}PP	Mix 4 w/c 0.40 0kg/m^{3}PP	Mix 5 w/c 0.40 0.2kg/m^{3}PP	Mix 6 w/c 0.40 1kg/m^{3}PP
Series 1						
Large slabs, horizontal, unloaded test	0	70(172)*	67(185)			
Small slabs (unrestrained)	0	38	42			
	0	50	38			
	0	50	35			
Small slabs (restrained)	0	65	46			
	0	53	69			
	0	58	60			
Wedge Slabs	0	22	22			
	0	38	32			
	0	25	42			
Small ring specimens, Gunma University type	0	40	0			
	0	27	0			
Unreinforced loaded slabs, Edinburgh University type**			F9			
			F12			
			F13			
Unreinforced slabs, Cracow University type			31			
			18			
Series 2						
Large slabs, vertical, loaded test				72	76	0
Small slabs (restrained)				56	0	0
				82	45	0
Medium size ring specimens				85	62	0
				73	52	0
				80	70	0

** 70(172) means 70 mm average and 172 mm in one cavity on the large slab.*
*** After the first spall the tests are terminated with this method.*

During the test of the large slabs exposed to the hydrocarbon fire curve fire in series no 1, spalling started in the two specimens without PP fibers after a very short exposure time, and after 4 minutes the whole fire exposed surface was spalled off. Spalling then continued intensely until the reinforcement was uncovered after less than 10 minutes. After 15 minutes no major events happened on large parts of the fire exposed surface except on two spots. The decrease in spalling intensity was probably caused by the heating up of the reinforcement which led to much less restrain and more thermal bowing developed of the whole specimen which led to crack development and stress release. When observing this behaviour, when spalling is first very intense and then rapidly decreases, a relevant question is what the behaviour would have been if the whole element is restrained or the size of the element is substantially large then the fire so a cold restraining frame is created. In these cases, there is a substantial risk for continuous flaking away of the whole cross section. This limits the applicability of the results from the test to only be relevant for assessing the spalling behaviour of the concrete cover, i.e. when the reinforcement gets hot the restraining effects not included in the test are taking over. Spalling results from large slab specimen tested without load or restraint cannot be used for a general assessment of spalling beyond the reinforcement layer if loads or restrains are expected in the real case.

Furthermore, during the test on large slabs one zone of each specimen spalling continued in a spot with very low intensity until the termination of the test after 60 minutes, see Figure 16. The reason for this spot wise spalling with a diameter of around 30 cm digging out a cavity in the specimen is difficult to know in detail. A possible explanation is that these zones were less cracked then the rest of the specimen so higher stresses were created during heating. This spalling in cavities also indicates that spalling beyond the reinforcement layer can and should not be assessed with this test setup.

Figure 16. Spalling continues beyond the reinforcement in a spot on both large slabs without PP fibres tested in series 1.

The test of wedged slabs was designed with two-sided fire exposure on a specimen with a changing thickness. The setup was aimed to reproduce what is happening in the web of beams where it is known from experimental studies that thin webs are more prone to spalling than thick ones. This was simulated by having a changing thickness. The idea was that the thin parts were much more sensitive to spalling then the thicker parts. Thus, this type of specimen could give a type of spalling thermometer. These specimens did not perform as intended, instead the upper thicker parts of the specimens spalled which probably is an indication that the reinforcement net in the centre of the specimen was not representative enough regarding load and restrain situation in a web of a beam. The spalling of the upper parts instead became an illustration of the fact that restraint from inner cold parts make surface spalling more probable. Also as all nine specimens were tested at once all sides of the specimens could not be observed during the test making the times of first occurrence of spalling imprecise.

The small ring specimens, Gunma type, showed a different result compared to the other tests as only mix 2 spalled and not mix 3. In all other tests mix 3 also spalled. The reason for this is difficult to know why this indicates that this shape and diameter is not suitable as a screening test method if the goal is to represent larger slab type specimens.

During the tests on small loaded slabs of Edinburgh type, the test was ended when the first spall occurred which makes this type of test a type of on/off test with additional observations of the time and size of first spall.

All results on spalling from the test series 1 are summarized in Figure 17. None of the tests on mix 1 with 1 kg/m³ PP fibres included spalled. Also, the small ring specimens of Gunma type mix 3 did not spall. In Figure 18 and 19 results from the two mixes that spelled are separated in one diagram each.

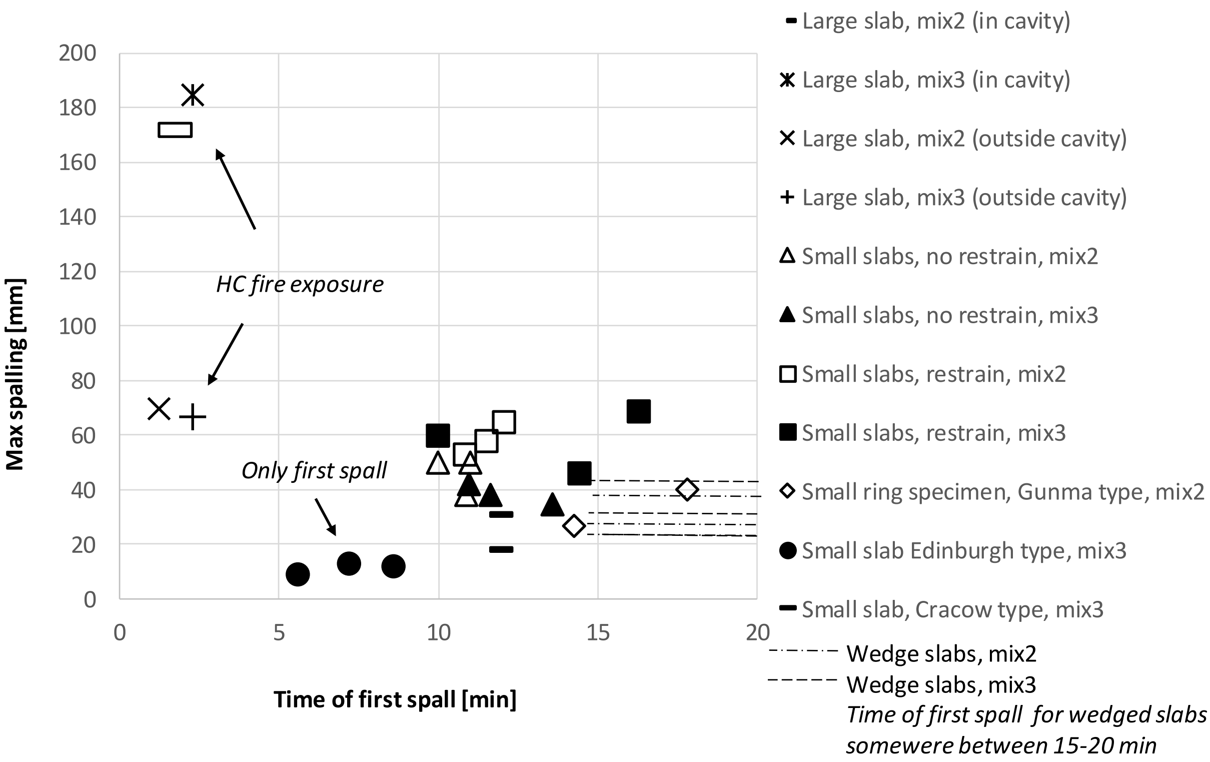

Figure 17. Spalling time and maximum spalling depths for all specimens that spalled in test series 1. All specimens, except when indicated, were exposed to the standard fire curve and were fire exposed until spalling stopped.

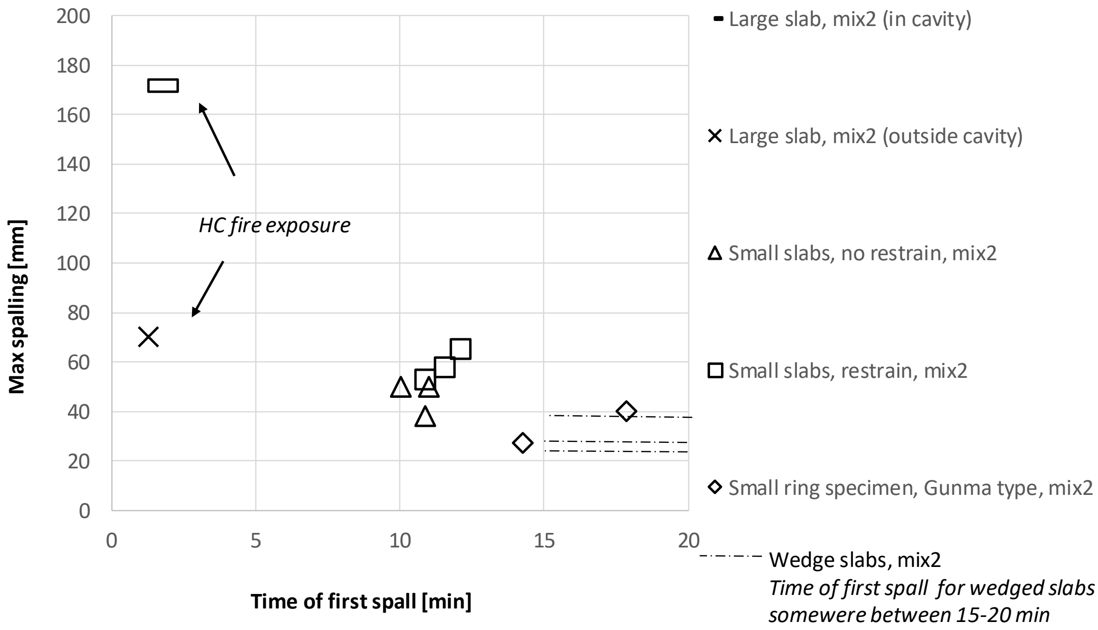

Figure 18. Spalling time and maximum spalling depths for specimens mix2 that spalled in test series 1. All specimens, except when indicated, were exposed to the standard fire curve and were fire exposed until spalling stopped.

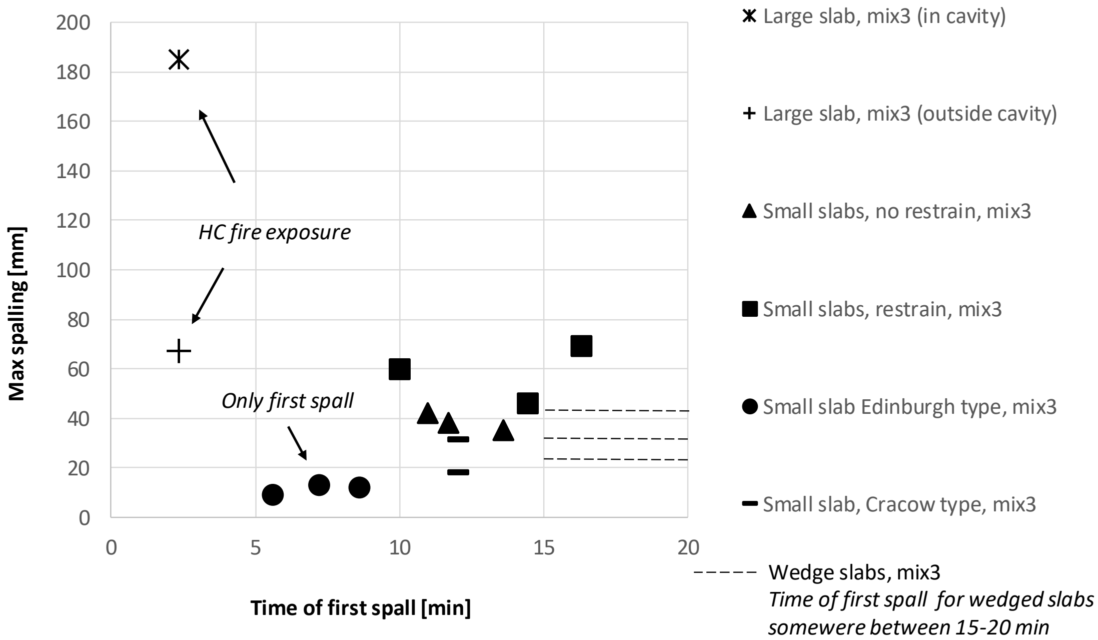

Figure 19. Spalling time and maximum spalling depths for specimens mix3 that spalled in test series 1. All specimens, except when indicated, were exposed to the standard fire curve and were fire exposed until spalling stopped. Gumma type specimens (small ring specimens) of mix 3 did not spall.

In the second step of the test campaign it was decided to include the restraint small slabs and a larger ring specimen of the Gunma type. Also in this second step of the program loaded large elements tested on the vertical furnace was included as a comparison.

Results in test series 2 showed that all specimens without PP fibers, mix 4, spalled with all three test methods. When testing the mix with 0.2 kg/m^3 PP fibres, mix 5, one of the small restrained slabs did not spall whereas all three large ring specimens and the loaded large slab did spall. All results can be seen in Figure 20 and in Table 6. Based on the result that one of the small restrained slabs of mix 5 did not spall the large ring specimen was shown to be the most representative test method compared with the large loaded slabs.

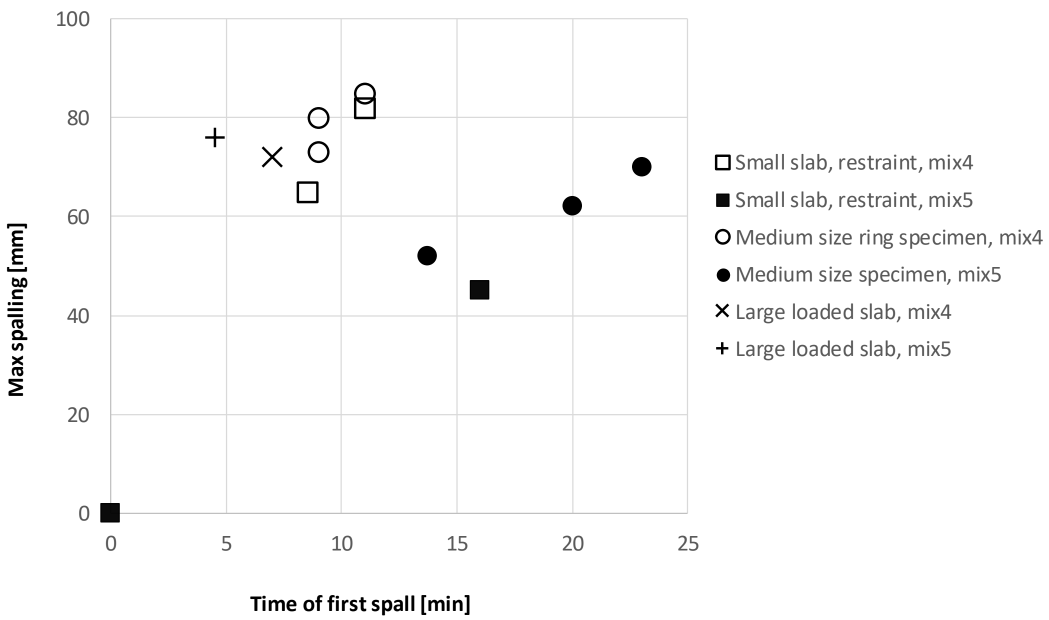

Figure 20. Spalling time and maximum spalling depths for all specimens that spalled in test series 2 with an addition of the small restraint slab of mix 5 that did not spall.

6 Discussion

A variety of different screening test methods are possible to use when the mix is highly prone to spalling, i.e. every medium size method indicates spalling no matter what cross section or load that is used as long as the heat load is large enough. But when dealing with mixes on the boarder the influence from different factors are more important. In general fire spalling of concrete is a phenomenon influenced by a vast number of factors. These influencing factors can be divided in three main groups, i) boundary conditions, ii) cross section design and iii) material related factors.

Boundary conditions are both the mechanical boundary, including external loads and restraint, and the thermal boundary. When the cross section is loaded in compression the risk for fire spalling is usually higher and rapid heating has also in many cases been shown to increase the propensity to spall.

The design of the cross section also influences the spalling phenomenon. Reinforcement that restricts crack development in the zone where tensile stresses develop during heating leads to a higher spalling propensity, Meyer-Ottens C. (1972). Also, cross sections heated from two sides like beams with thin webs have been seen to spall in a violent way, Meyer-Ottens C. (1972), Jansson R., Boström L, (2011).

Material related factors include both mix design and the current state of the material. Regarding the mix design there are four main influencing factors, i) the type of aggregate, ii) the water/cement ratio, iii) filler additions and, iv) the addition of polypropylene fibres to the mix. The current state of the material includes the strength, permeability and the moisture profile which are all influenced by the conditioning from the day of moulding until the day of heat exposure.

It is thus still not possible through small or medium size test set-ups possible to determine how a concrete exposed to fire will spall in a real life situation. The reason for this is that the boundary conditions and the cross section design will be different, and both these factors influence the spalling behaviour. There are, however, small or medium size test set-ups that can be used for screening different concretes with the aim to find concretes that will have a good chance to show a very limited amount of fire spalling in practice. The best option found in the present study is the medium size ring specimen, where the concrete is moulded in steel rings. These rings will restrain the thermal expansion, and thus limit the crack formation. The circular shape shows a better correlation to the results obtained with the large slab specimens compared to the rectangular restrained specimens. The reason for this is not fully known, but one factor could be that the ring shaped specimens were moulded directly into the reinforcing ring while for the rectangular specimens a mortar had to be used to fill out a space between the reinforcing steel structure and the concrete specimen. Another factor that could affect the behaviour is the actual shape, i.e. the ring shape gives a boundary condition that simulates the behaviour of the large specimens in a better way. But, as the results from smaller ring shape specimens was shown to not correspond to the larger tests the size of the steel rings seems to be important.

7 Conclusions and recommendation

Several different small and medium size test set-ups and specimen geometries have been examined experimentally. The main characteristic examined has been the spalling behaviour. In addition to the small/medium size specimens some large scale tests have been performed with the same type of concretes in order to compare the spalling behaviour of the small/medium size specimens and the large ones.

The results from previous studies, Boström L. (2004) and show that with restrained specimens the correlation with the behaviour of the large specimens is better, and the best correlation was in this study obtained with the medium size ring shaped test specimen. Two different ring shaped specimens were examined, and the results show that the size may be important and the best results were obtained with the 600 mm diameter and 300 mm high specimen. This specimen also has other advantages, it is very simple and fast to manufacture, and thus it is relatively cheap. The tests can be performed on small size furnaces.

These medium size ring specimens where equipped with reinforcement nets made of 12 mm bars with 150 mm distances mounted 50 mm from the upper and lower sides of the slabs. A recommended further development is to use only one reinforcement net made of 8 mm diameter reinforcement bars with the distance 100 mm placed on the depth 100 mm from the fire exposed surface. This net should be welded to the sides of the specimen to ensure that the specimen stays inside the pipe and can be used as a reference point for temperature measurements if studies of thermal performance is done.

8 References

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EN 1365-series Fire resistance tests for loadbearing elements

EN 13381-3:2015 Test methods for determining the contribution to the fire resistance of structural members – Part 3: Applied protection to concrete members

SP Fire 119 Fire resistance tests of building structures in small scale (in Swedish)

Appendix A - Results series no 1

Summary of test samples test series no 1

Test method	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Series no 1						
Large slabs, horizontal, unloaded test	1	1	1			
Small slabs (unrestrained)	3	3	3			
Small slabs (restrained)	3	3	3			
Wedge slabs	3	3	3			
Ring specimens, Gunma University type	2	2	2			
Unreinforced loaded slabs, Edinburgh University type			3			
Unreinforced slabs, Edinburgh University type			2			

Small Slabs, unstrained, series no1

Small slab, unrestrained, 13: 500x600-400 Mix 1: 0.33-1.0kgPP

The test was performed December 7, 2016.

Time [min:s]	**Observations** **(refer to the non-flame side if nothing else is stated)**
00:00	The test starts.
15:00	Some water is visible on one vertical side.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

No spalling measurements were made since no spalling occurred during the test.

Figure A1. Test specimen during the test.

Figure A2. Test specimen after the test.

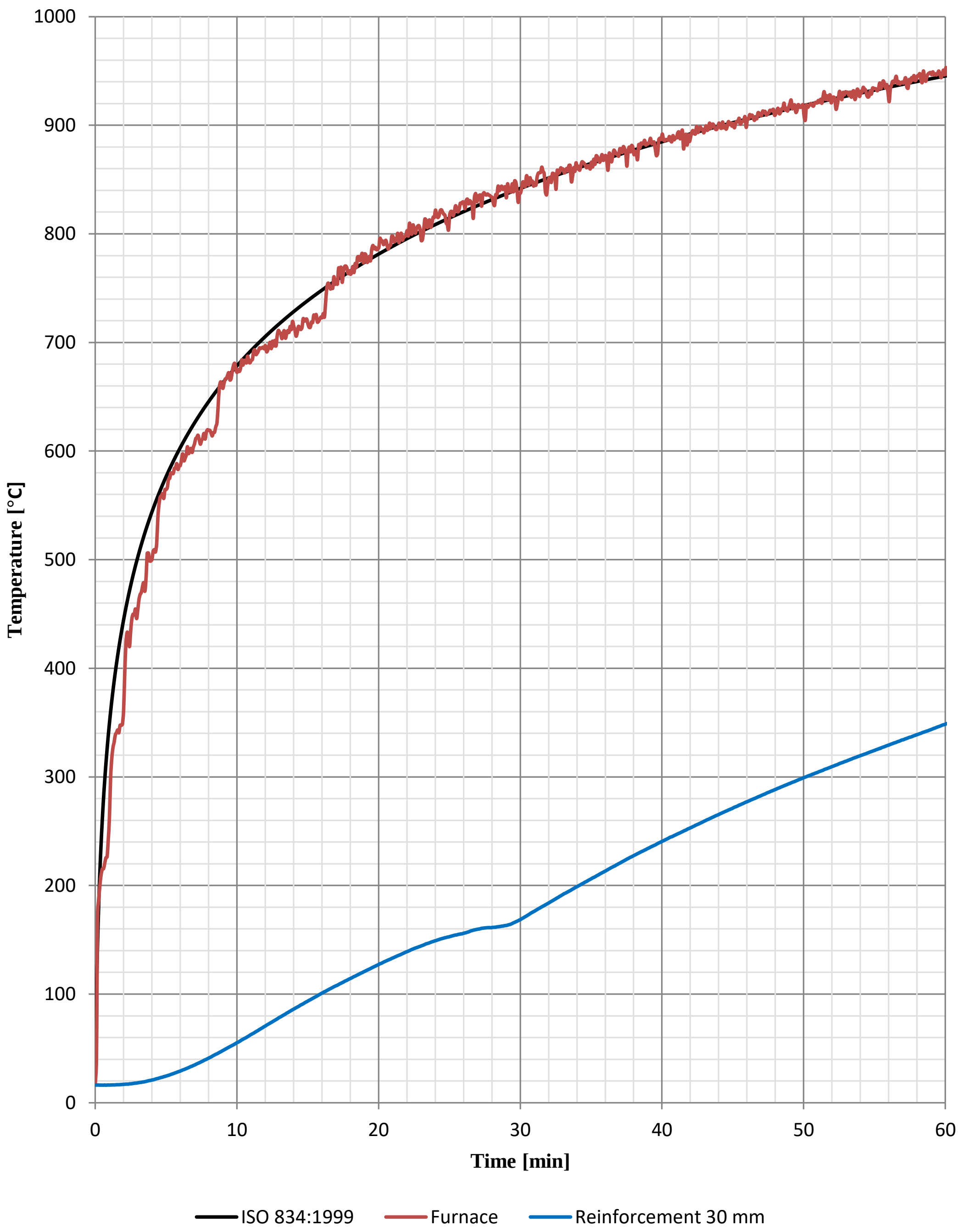

Figure A3. Measured temperatures during the test.

Small slab, unrestrained, 14: 500x600-400 Mix 1: 0.33-1.0kgPP

The test was performed December 7, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
17:00	The thermocouple fixed to the reinforcing net at 30 mm from the fire exposed surface is out of order. Some water is visible at the vertical sides.
60:00	Water is visible at the vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
272.2	269.8	0.9	-

Figure A4. Test specimen during the test.

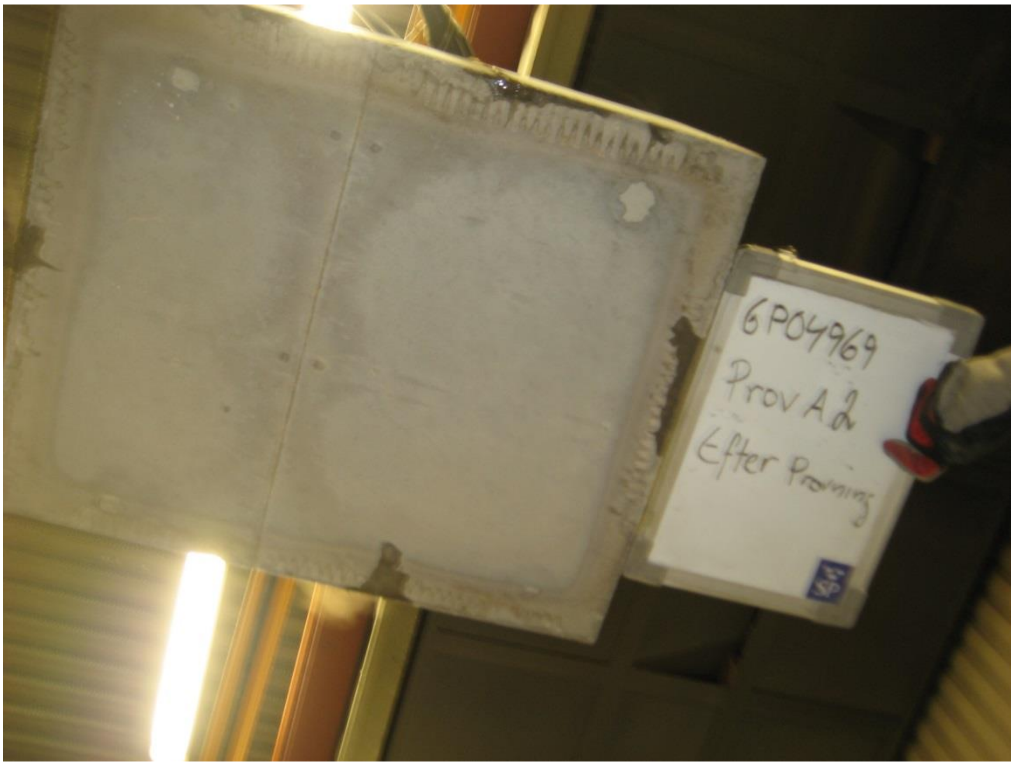

Figure A5. Test specimen after the test.

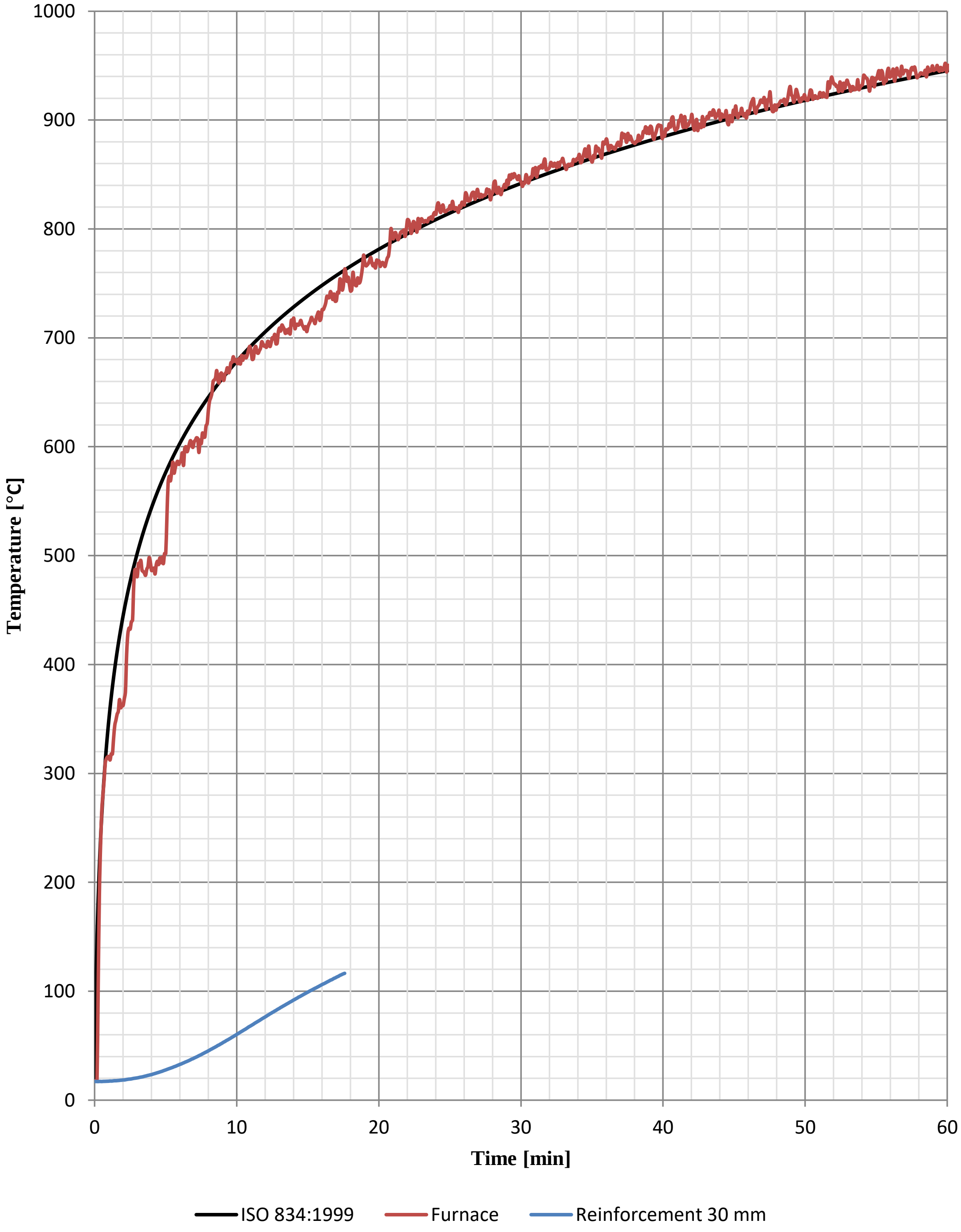

Figure A6. Measured temperatures during the test. The thermocouple Reinforcement 30 mm was out of order after 17,8 minutes of the test.

Small slab, unrestrained, 15: 500x600-400 Mix 1: 0.33-1.0kgPP

The test was performed December 9, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
20:00	Some water is visible on three vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
275.0	272.8	0.8	-

Figure A7. Test specimen during the test.

Figure A8. Test specimen after the test.

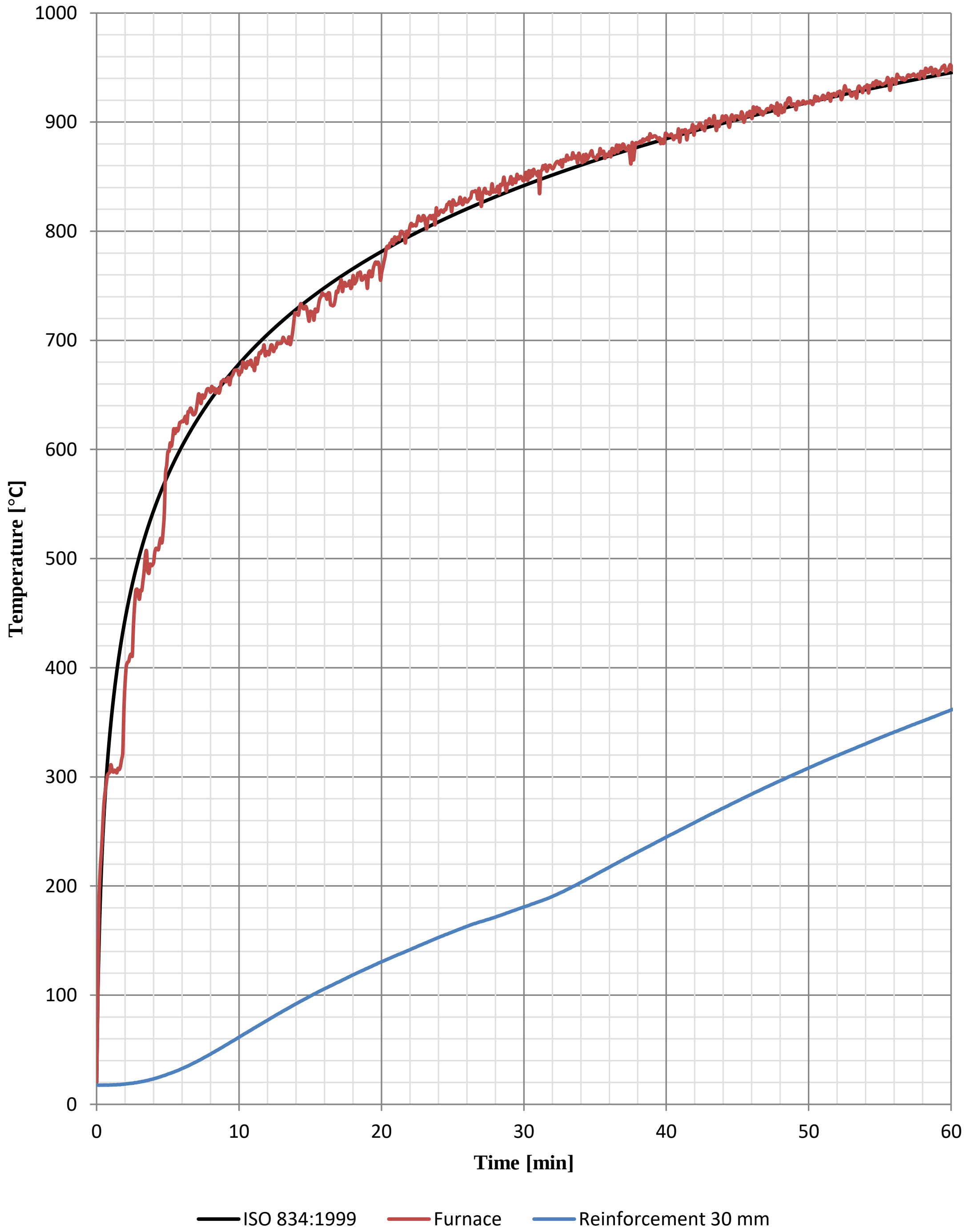

Figure A9. Measured temperatures during the test.

Small slab, unrestrained, 1: 500x600-400 Mix 2 0.33-0.0kgPP

The test was performed December 9, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
10:50	A bang is heard from the test specimen.
13:00	A bang is heard from the test specimen.
13:50	Two bangs are heard from the test specimen.
15:00	Small bangs are heard from the test specimen, continuous spalling.
20:00	Some water is visible on all vertical sides.
≈ 24:00	The spalling ends.
30:00	Some water is visible on all vertical sides.
60:00	Water on all vertical sides.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
294.4	285.0	3.2	38

Figure A10. Test specimen during the test.

Figure A11. Test specimen after the test.

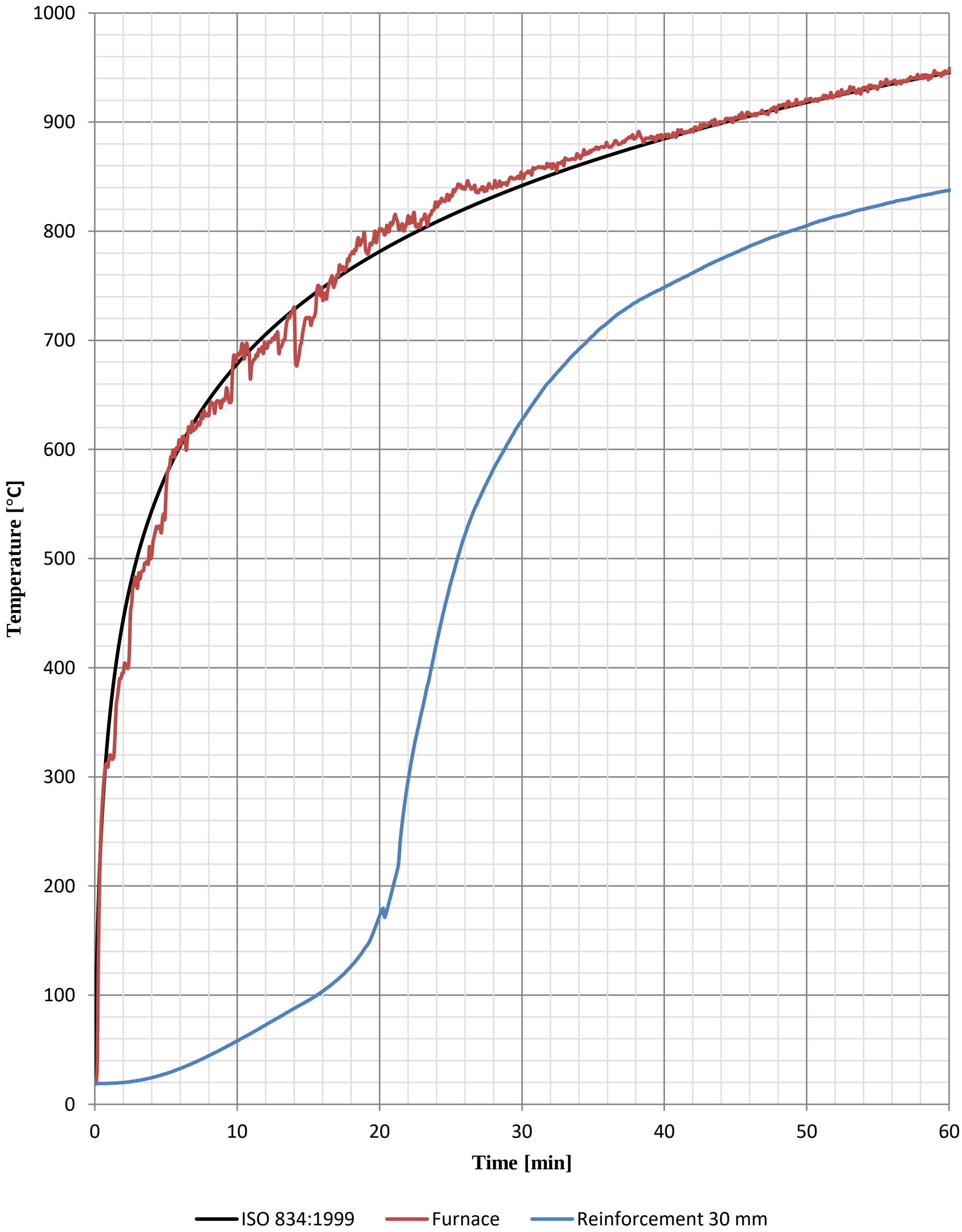

Figure A12. Measured temperatures during the test.

Small slab, unrestrained, 2: 500x600-400 Mix 2 0.33-0.0kgPP

The test was performed December 13, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
10:00	A small bang is heard from the test specimen.
10:45	A small bang is heard from the test specimen.
11:35	A bang is heard from the test specimen.
12:00	A small bang is heard from the test specimen.
12:20	Small bangs are heard from the test specimen, continuous spalling.
20:00	Water is visible on three vertical sides.
26:30	The spalling ends.
30:00	Some water is visible on all vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
289.4	276.4	4.5	50

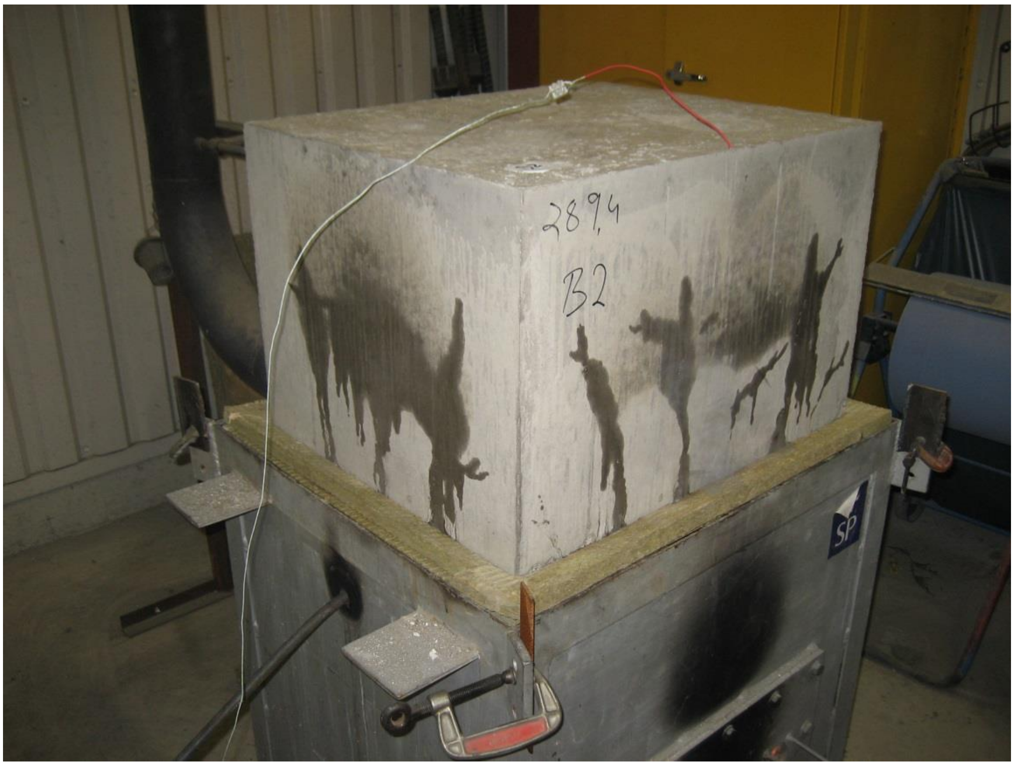

Figure A13. Test specimen during the test.

Figure A14. Test specimen after the test.

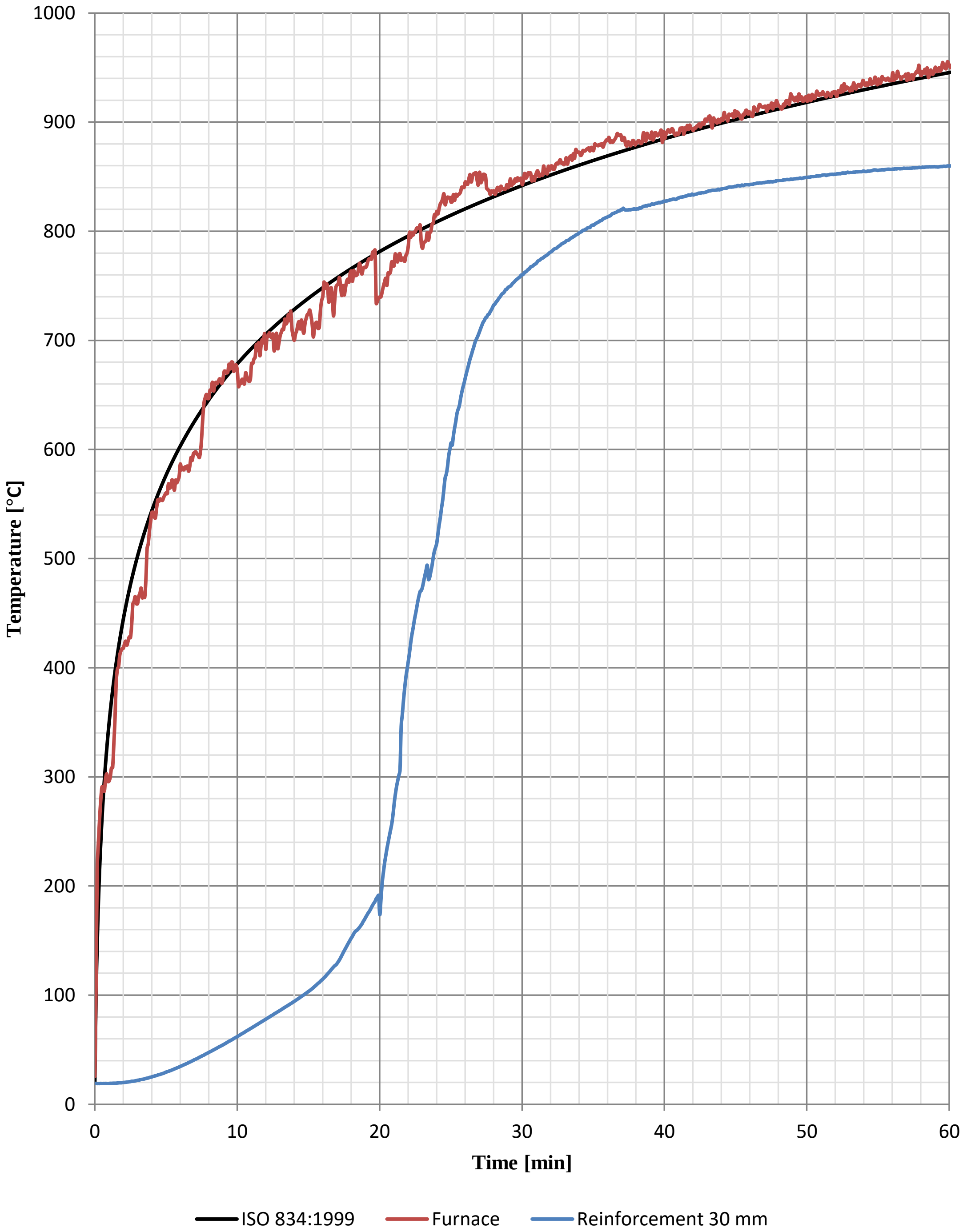

Figure A15. Measured temperatures during the test.

Small slab, unrestrained, 3: 500x600-400 Mix 2 0.33-0.0kgPP

The test was performed December 13, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
11:00	A bang is heard from the test specimen.
12:10	A small bang is heard from the test specimen.
12:30	Two bangs are heard from the test specimen.
12:55	A bang is heard from the test specimen.
13:35	A loud bang is heard from the test specimen.
14:00	Small bangs are heard from the test specimen, continuous spalling.
26:00	The spalling ends. Water is visible on all vertical sides.
30:00	A continuous horizontal crack is visible on one vertical edge, approximately 50 mm from the fire exposed side.
60:00	Water is visible on all vertical sides.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
289.0	278.2	3.7	50

Figure A16. Test specimen during the test.

Figure A17. Test specimen after the test.

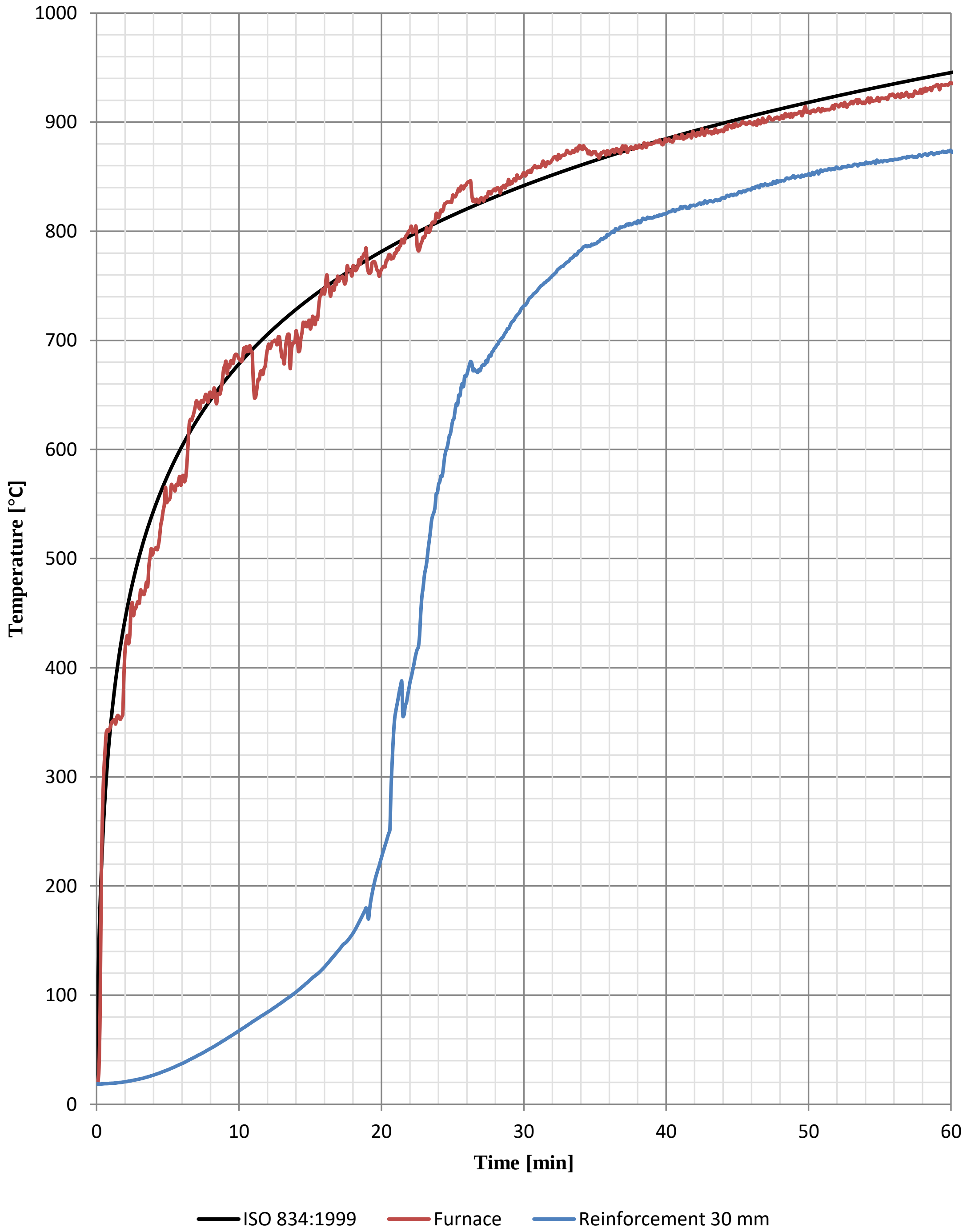

Figure A18. Measured temperatures during the test.

Small slab, unrestrained, 7: 500x600-400 Mix 3 0.40-0.0kgPP

The test was performed December 15, 2016.

Time [min:s]	**Observations** **(refer to the non-flame side if nothing else is stated)**
00:00	The test starts.
11:00	A bang is heard from the test specimen.
11:50	Two small bangs are heard from the test specimen.
12:20	A bang is heard from the test specimen.
12:40	A small bang is heard from the test specimen.
13:30	A small bang is heard from the test specimen.
13:50	A bang is heard from the test specimen.
14:50	Small bangs are heard from the test specimen, continuous spalling.
20:00	A horizontal cracks are visible, approximately 50 mm from the fire exposed side of the test slab, on two vertical sides. Some water is visible on three vertical sides.
27:00	The spalling ends, some water is visible on all vertical sides.
45:00	Water is visible on all vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	**Weight after [kg]**	**Weight reduction [%]**	**Maximum spalling depth [mm]**
273.8	261.8	4.4	42

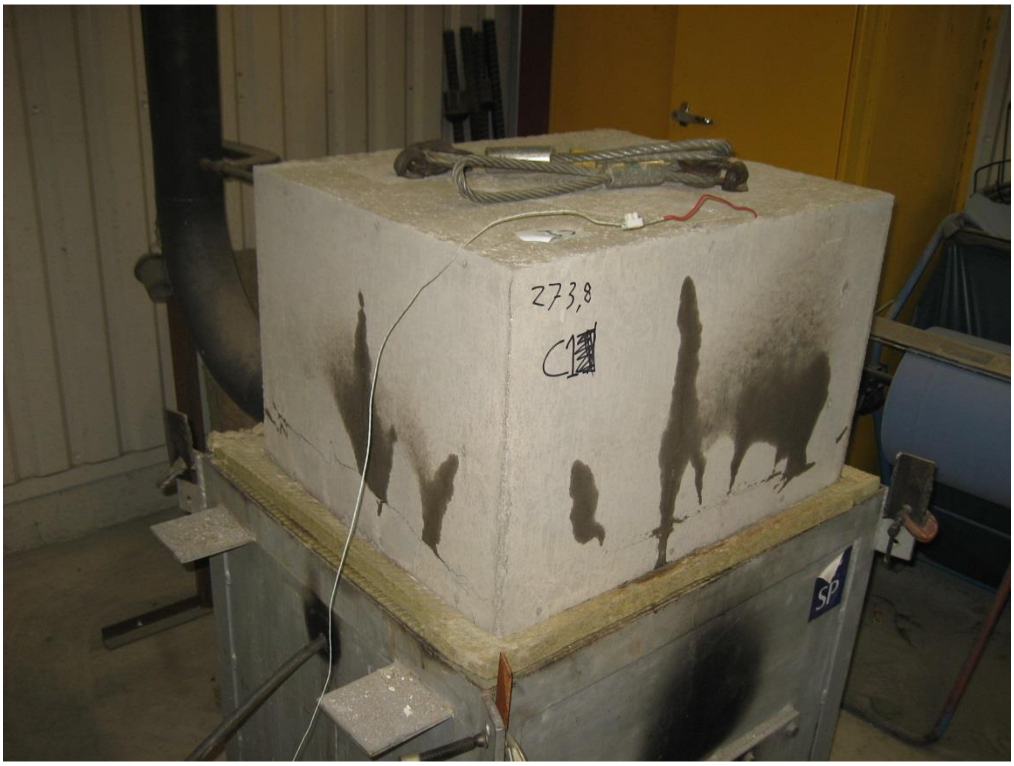

Figure A19. Test specimen during the test.

Figure A20. Test specimen after the test.

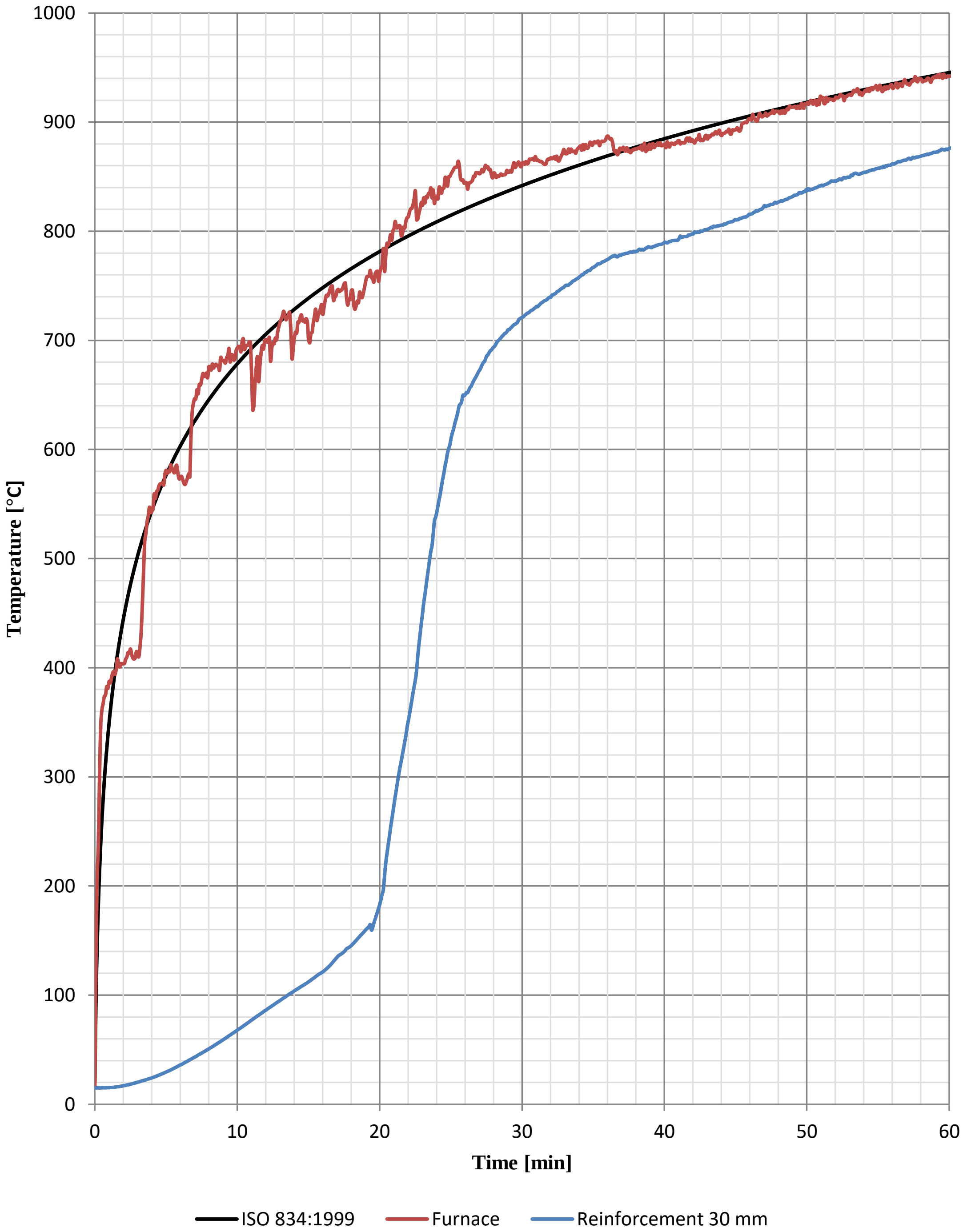

Figure A21. Measured temperatures during the test.

Small slab, unrestrained, 8: 500x600-400 Mix 3 0.40-0.0kgPP

The test was performed December 15, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
11:40	A bang is heard from the test specimen.
12:10	A bang is heard from the test specimen.
12:35	A bang is heard from the test specimen.
12:55	Two small bangs are heard from the test specimen.
13:40	Two small bangs are heard from the test specimen.
14:00	Small bangs are heard from the test specimen, continuous spalling.
20:00	Some water is visible on three vertical sides.
23:00	The spalling ends.
30:00	Water is visible on all vertical sides.
45:00	Water is visible on all vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
274.4	263.0	4.2	38

Figure A22. Test specimen during the test.

Figure A23. Test specimen after the test.

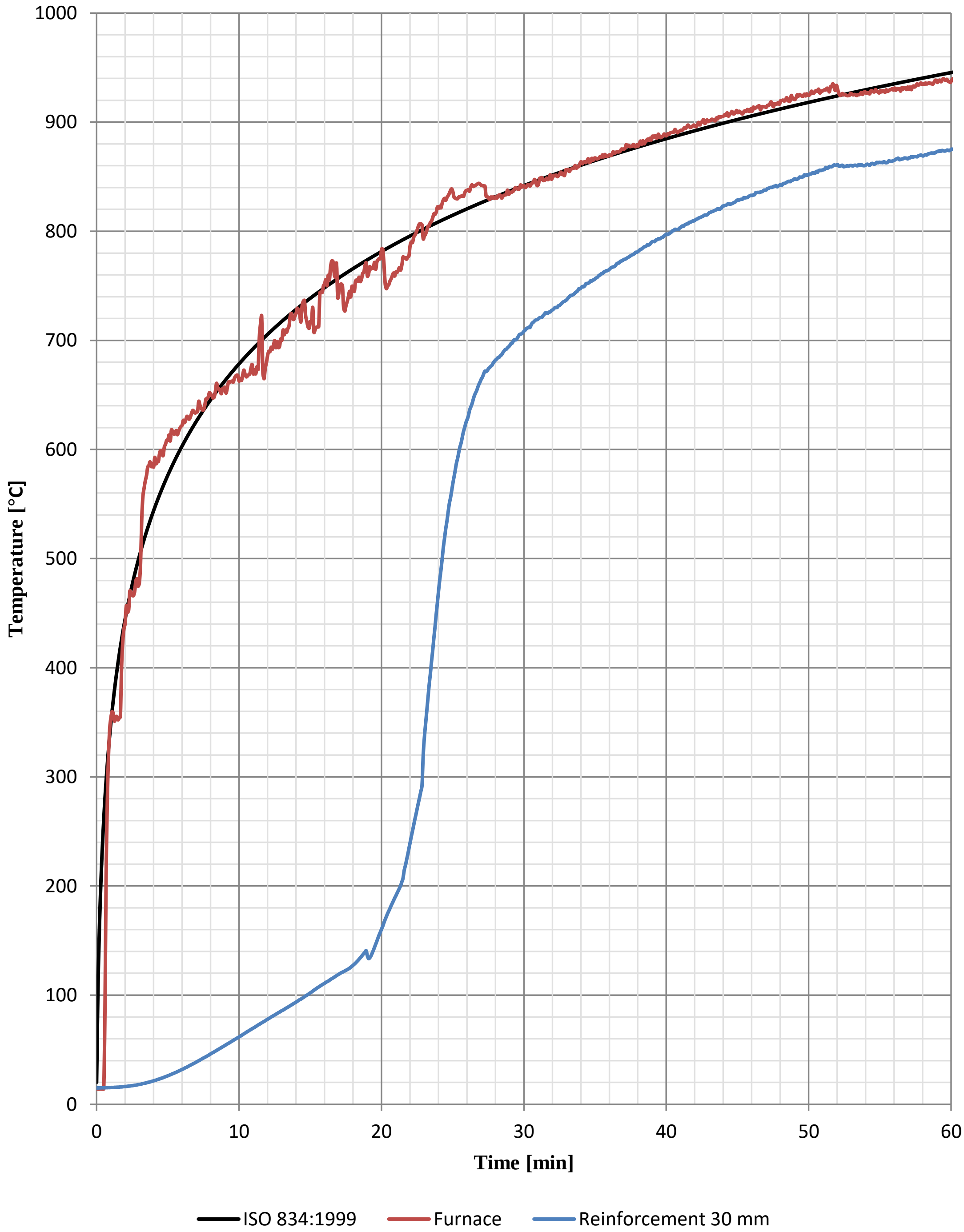

Figure A24. Measured temperatures during the test.

Small slab, unrestrained, 9: 500x600-400 Mix 3 0.40-0.0kgPP

The test was performed December 19, 2016.

Time [min:s]	**Observations** **(refer to the non-flame side if nothing else is stated)**
00:00	The test starts.
13:35	A bang is heard from the test specimen.
14:45	Two bangs are heard from the test specimen.
15:10	A small bang is heard from the test specimen.
15:25	A bang is heard from the test specimen.
16:00	Small bangs are heard from the test specimen, continuous spalling.
20:00	Some water is visible on three vertical sides.
27:00	The spalling ends.
30:00	Water is visible on all vertical sides.
45:00	Water is visible on all vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	**Weight after [kg]**	**Weight reduction [%]**	**Maximum spalling depth [mm]**
277	265.6	4.1	55

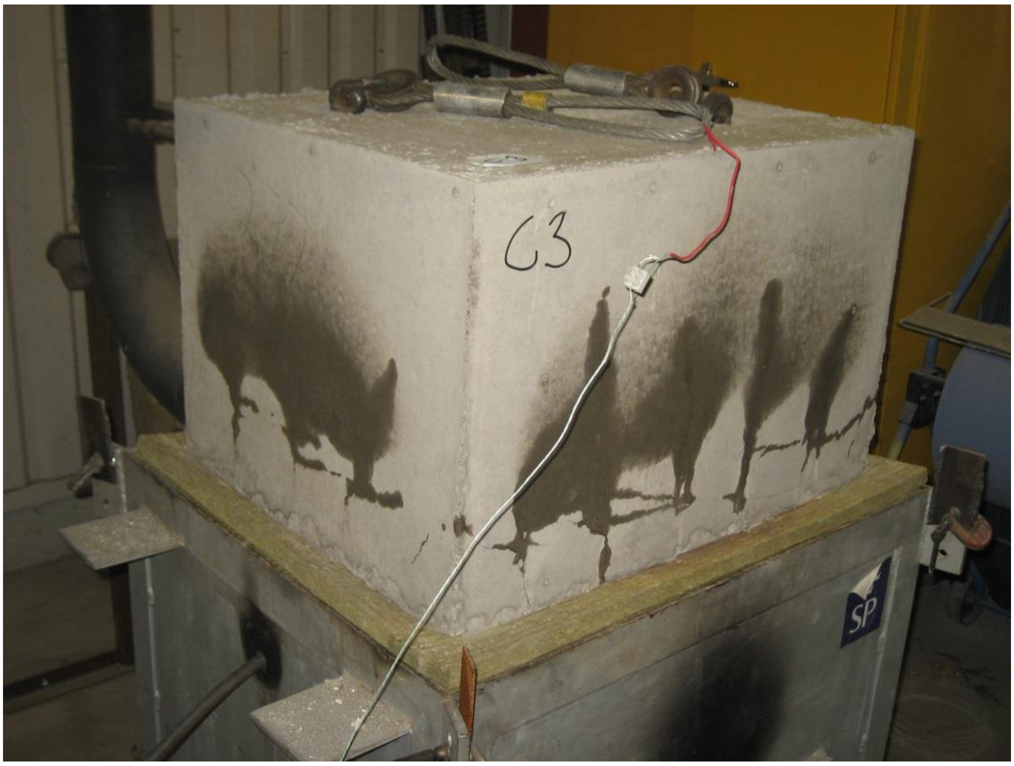

Figure A25. Test specimen during the test.

Figure A26. Test specimen after the test.

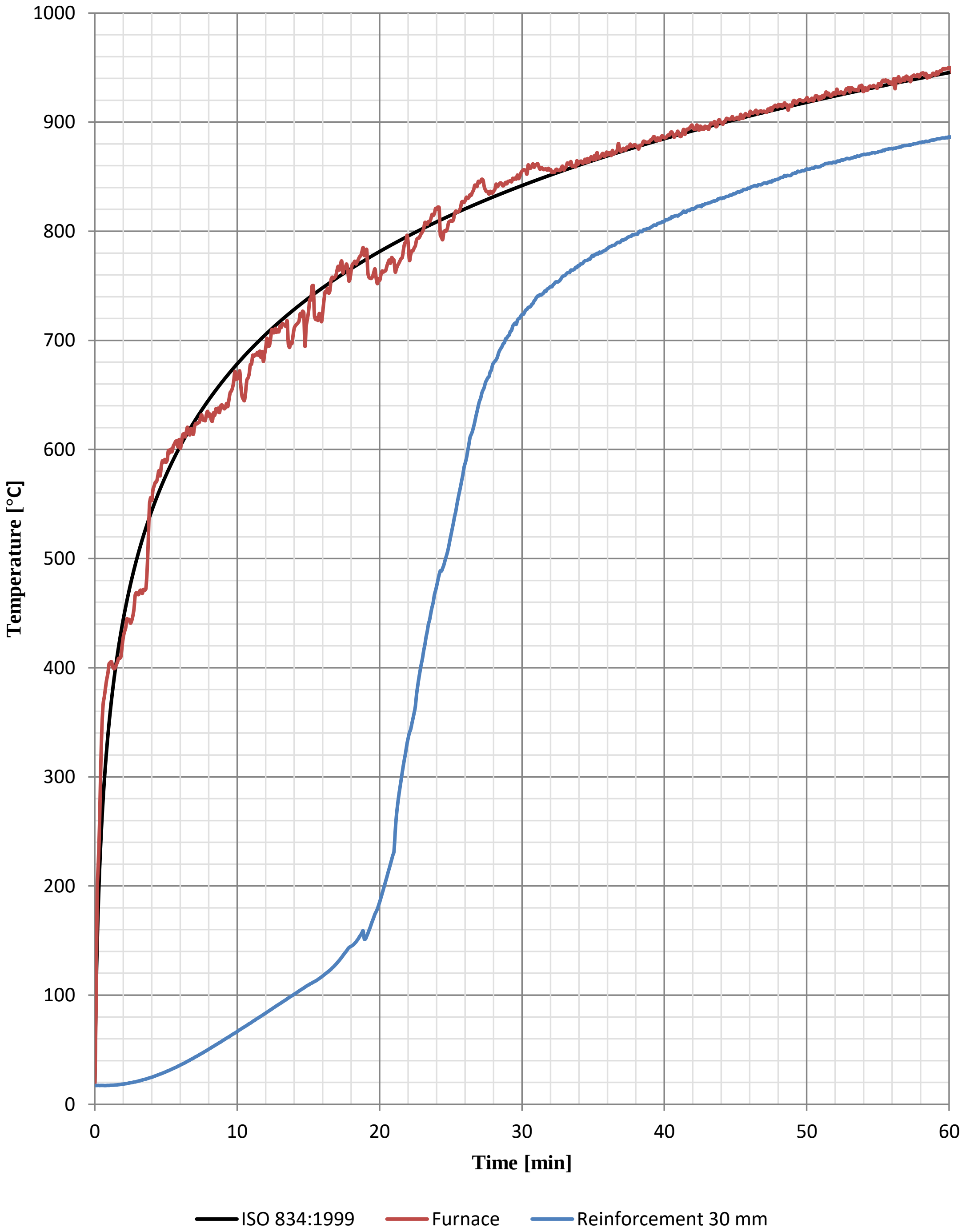

Figure A27. Measured temperatures during the test.

Small slabs, restrained, series no1

Small slab, restrained, 16: 500x600-400 Mix 1 0.33-1.0kgPP

The test was performed December 8, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
24:00	Some water is visible on a vertical side.
30:00	Some water is visible on all vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
371.4*	369.4*	0.5*	-

*Including the weight of the frame used for restraining the test slab

Figure A28. Test specimen during the test.

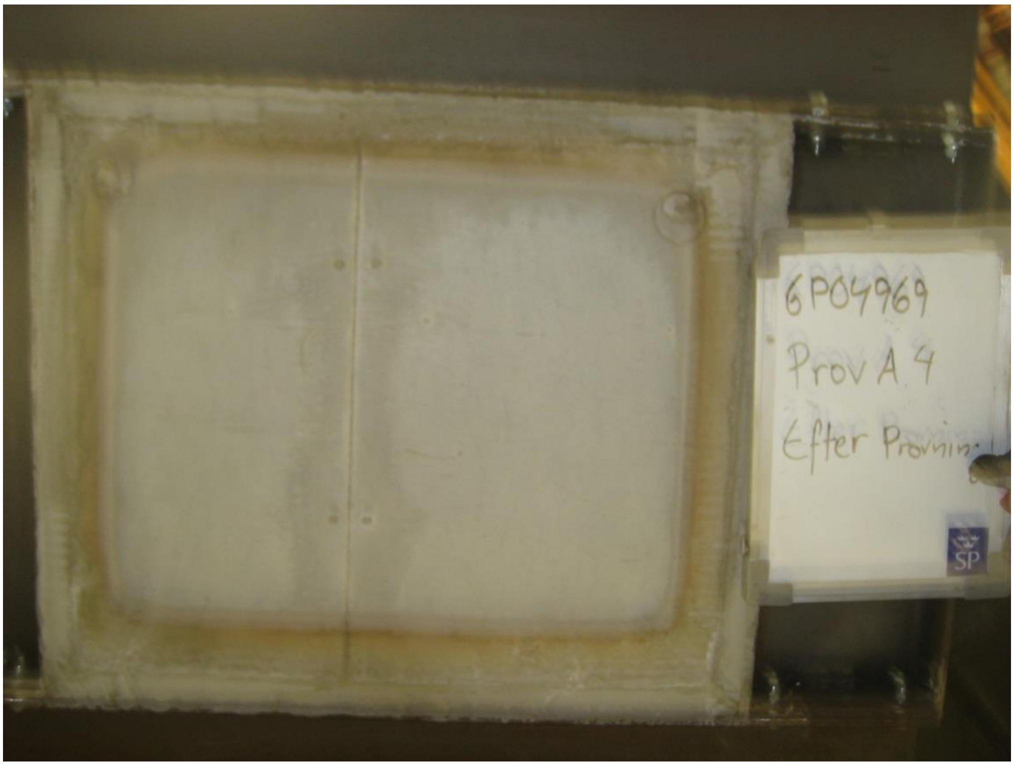

Figure A29. Test specimen after the test.

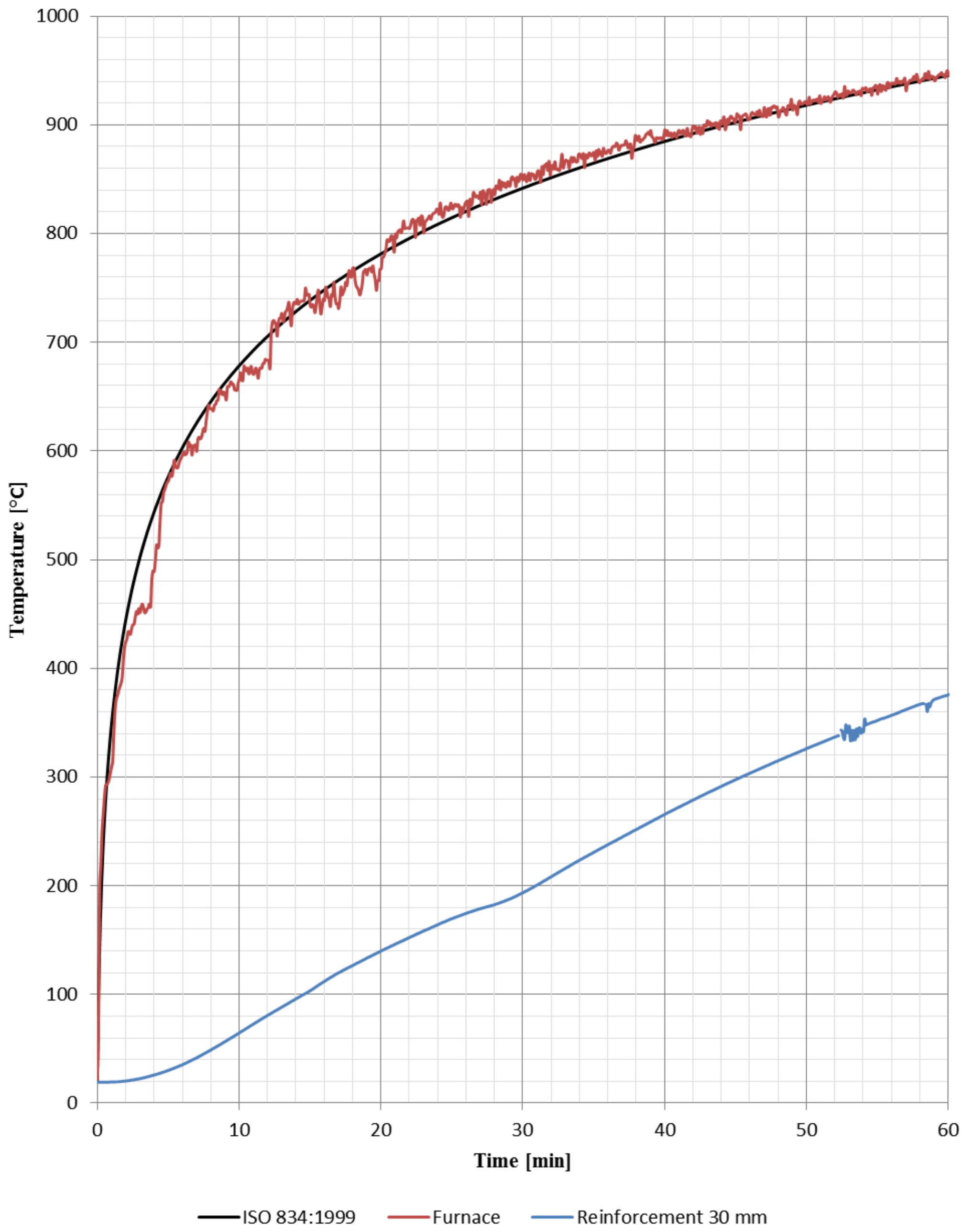

Figure A30. Measured temperatures during the test.

Small slab, restrained, 17: 500x600-400 Mix 1 0.33-1.0kgPP

The test was performed December 8, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
28:00	Some water is visible on three vertical sides.
36:00	Some water is visible on all vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

Since no spalling occurred during the test no spalling measurements were made.

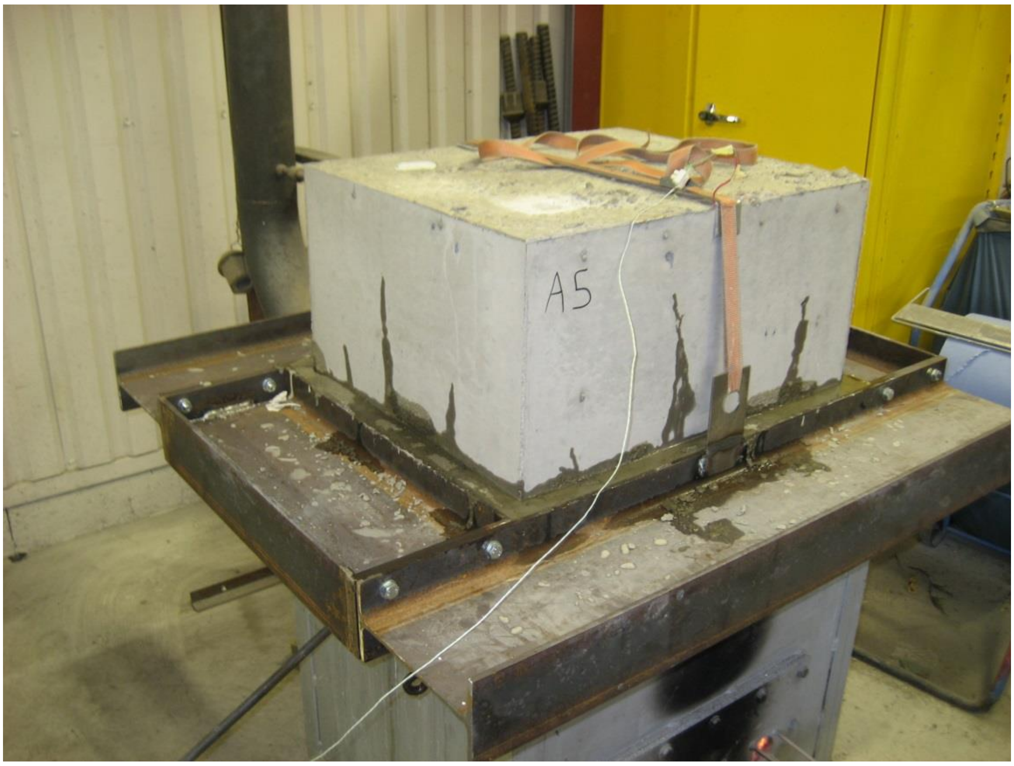

Figure A31. Test specimen during the test.

Figure A32. Test specimen after the test.

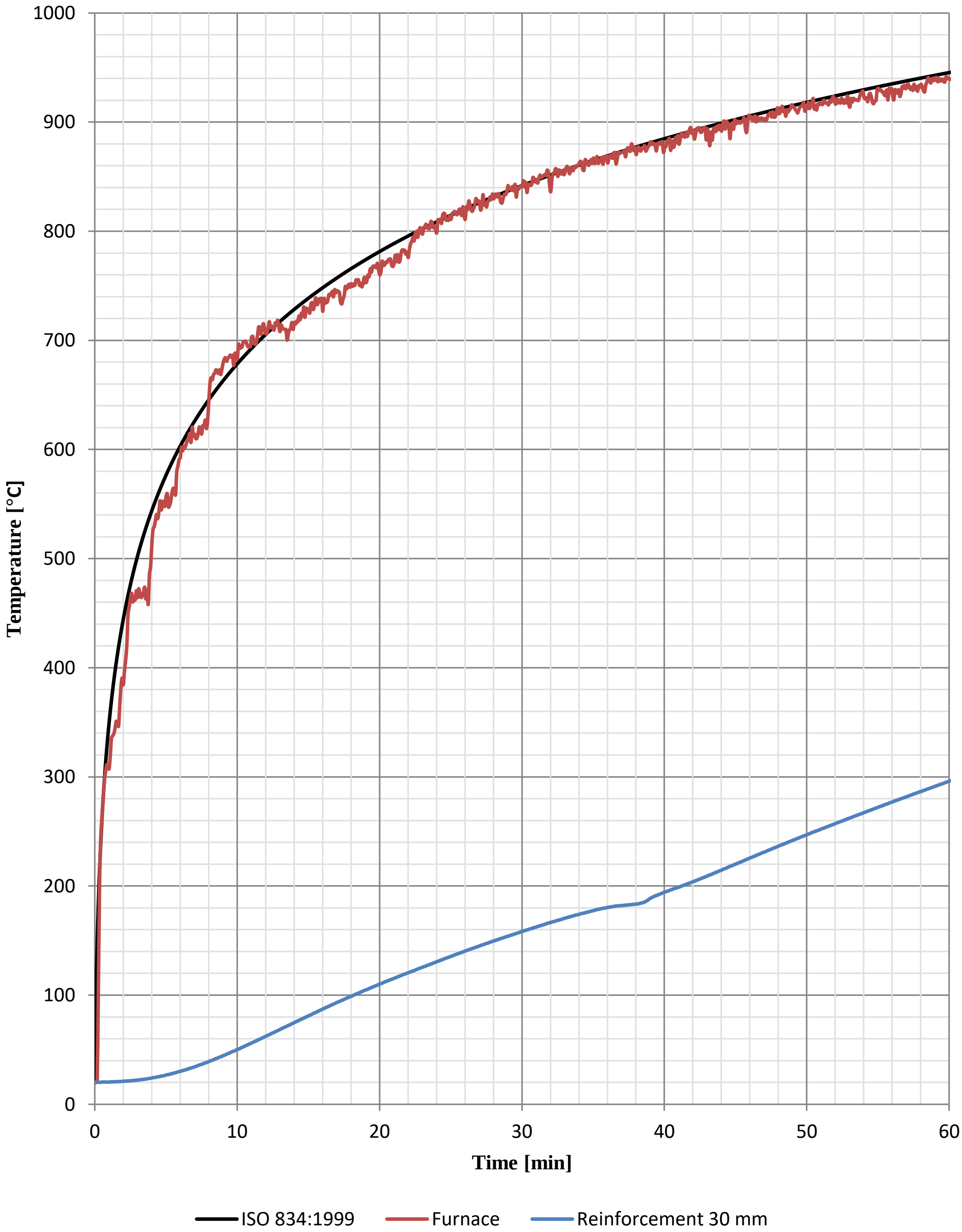

Figure A33. Measured temperatures during the test.

Small slab, restrained, 18: 500x600-400 Mix 1 0.33-1.0kgPP

The test was performed December 12, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
20:00	Some water on two vertical sides.
30:00	Some water on three vertical sides.
45:00	Some water on all vertical sides.
60:00	Some water on all vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
370.8*	368.2*	0.7*	-

*Including the weight of the frame used for restraining the test slab

Figure A34. Test specimen during the test.

Figure A35. Test specimen after the test.

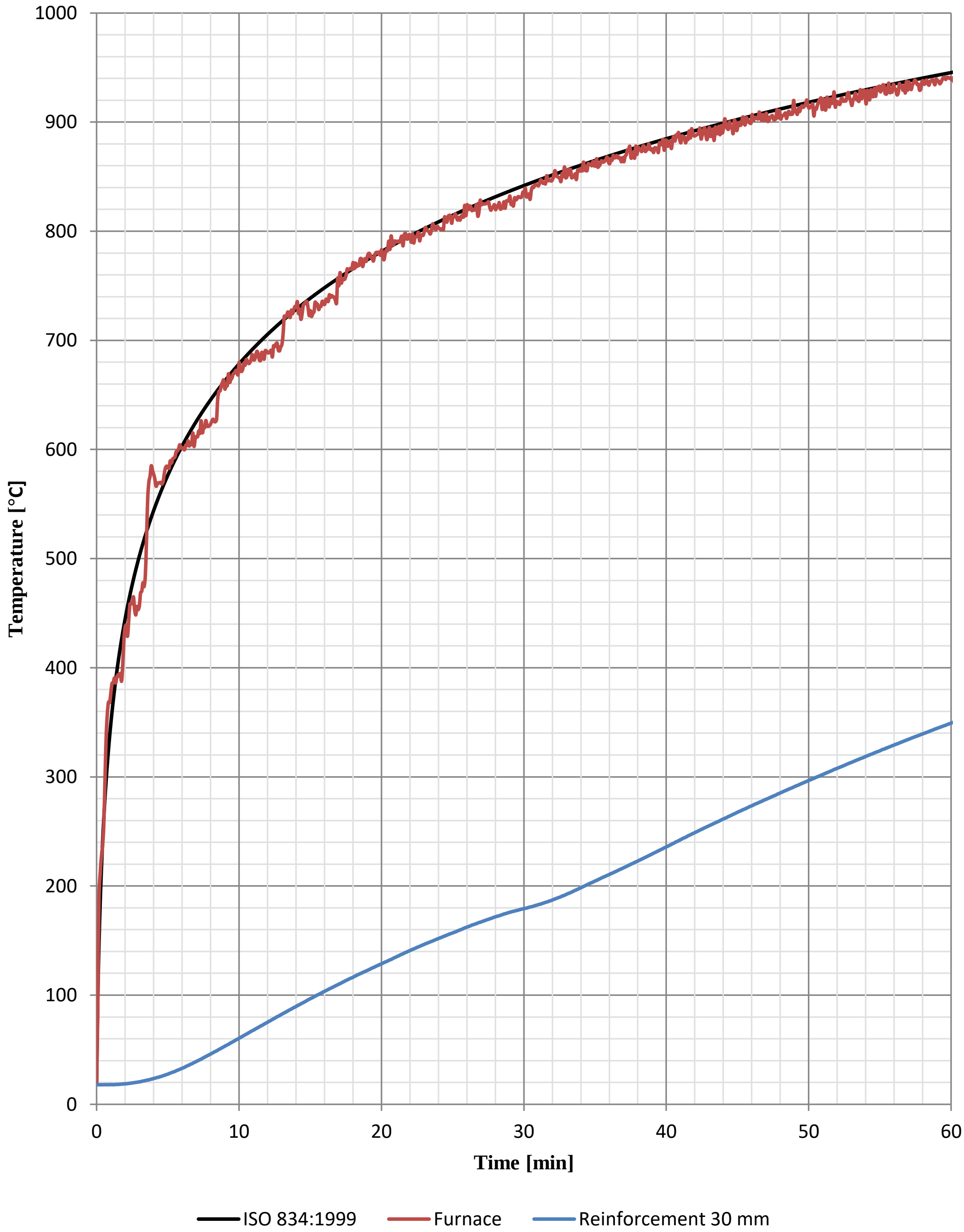

Figure A36. Measured temperatures during the test.

Small slab, restrained, 4: 500x600-400 Mix 1 0.33-0.0kgPP

The test was performed December 12, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
12:05	A bang is heard from the test specimen.
13:35	Two small bangs are heard from the test specimen.
14:10	Small bangs are heard from the test specimen, continuous spalling.
20:00	Some water is visible on one vertical side.
21:30	A louder bang is heard from the test specimen.
30:00	Some water is visible on all vertical sides.
31:00	The spalling ends.
45:00	Water is visible on all vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
386.2*	368.2*	4.7*	65

*Including the weight of the frame used for restraining the test slab

Figure A37. Test specimen during the test.

Figure A38. Test specimen after the test.

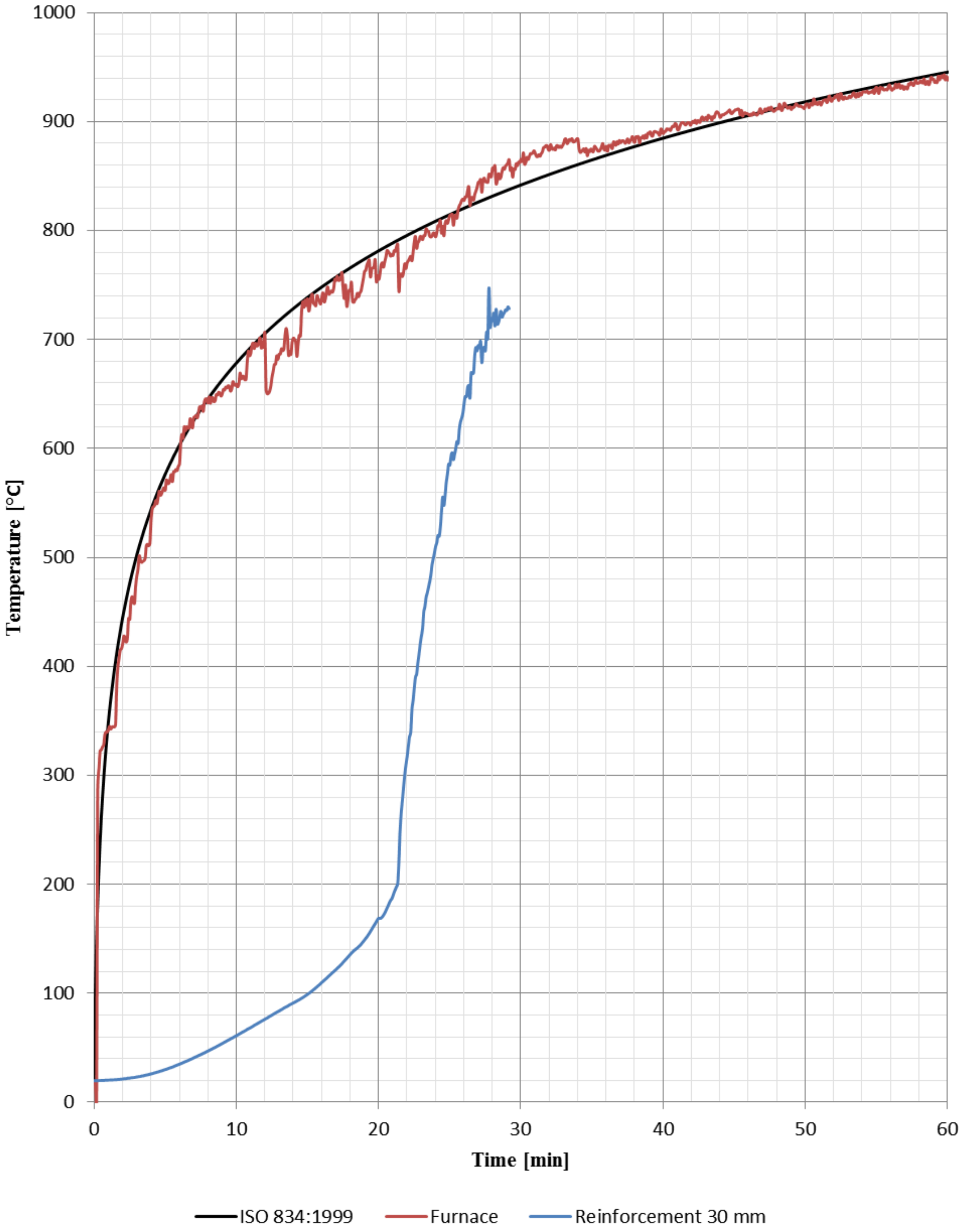

Figure A39. Measured temperatures during the test. The thermocouple Reinforcement 30 mm was out of order after 29,1 minutes of the test.

Small slab, restrained, 5: 500x600-400 Mix 1 0.33-0.0kgPP

The test was performed December 14, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
10:50	A bang is heard from the test specimen.
12:05	A louder bang is heard from the test specimen.
12:30	Small bangs are heard from the test specimen, continuous spalling,
20:00	Some water is visible on three vertical sides.
≈ 29:00	The spalling ends.
30:00	Some water is visible on all vertical sides.
32:10	A bang is heard from the test specimen.
45:00	Water is visible on all vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
383.8	370.2	3.5	53

*Including the weight of the frame used for restraining the test slab

Figure A40. Test specimen during the test.

Figure A41. Test specimen after the test.

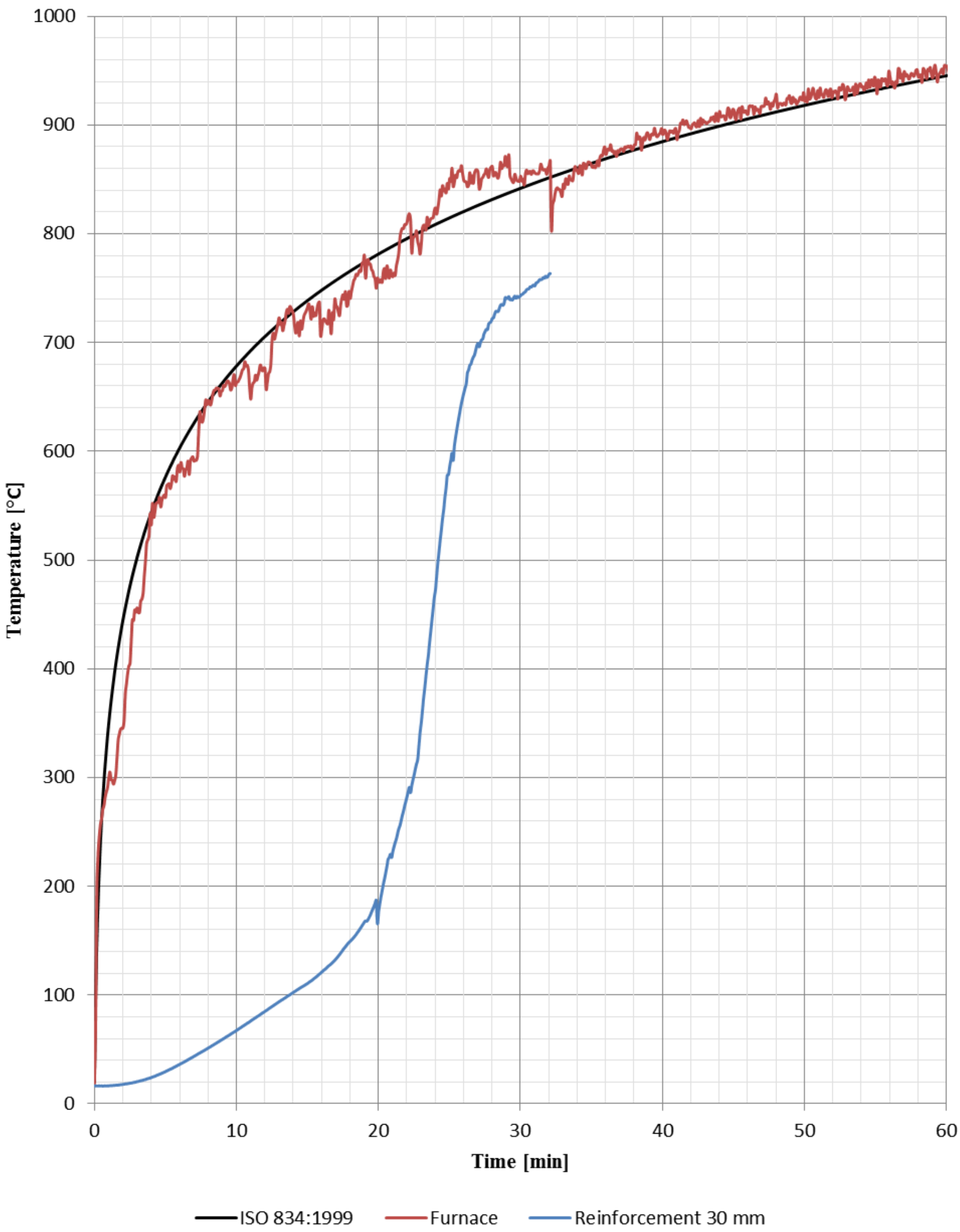

Figure A42. Measured temperatures during the test. The thermocouple Reinforcement 30 mm was out of order after 32,1 minutes of the test.

Small slab, restrained, 6: 500x600-400 Mix 1 0.33-0.0kgPP

The test was performed December 14, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
11:30	A bang is heard from the test specimen.
12:45	A bang is heard from the test specimen.
13:25	Small bangs are heard from the test specimen, continuous spalling.
20:00	Some water is visible on one vertical side.
30:00	The spalling ends, some water is visible on all vertical sides.
45:00	Water is visible on all vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
379.4	364.4	4.0	58

*Including the weight of the frame used for restraining the test slab

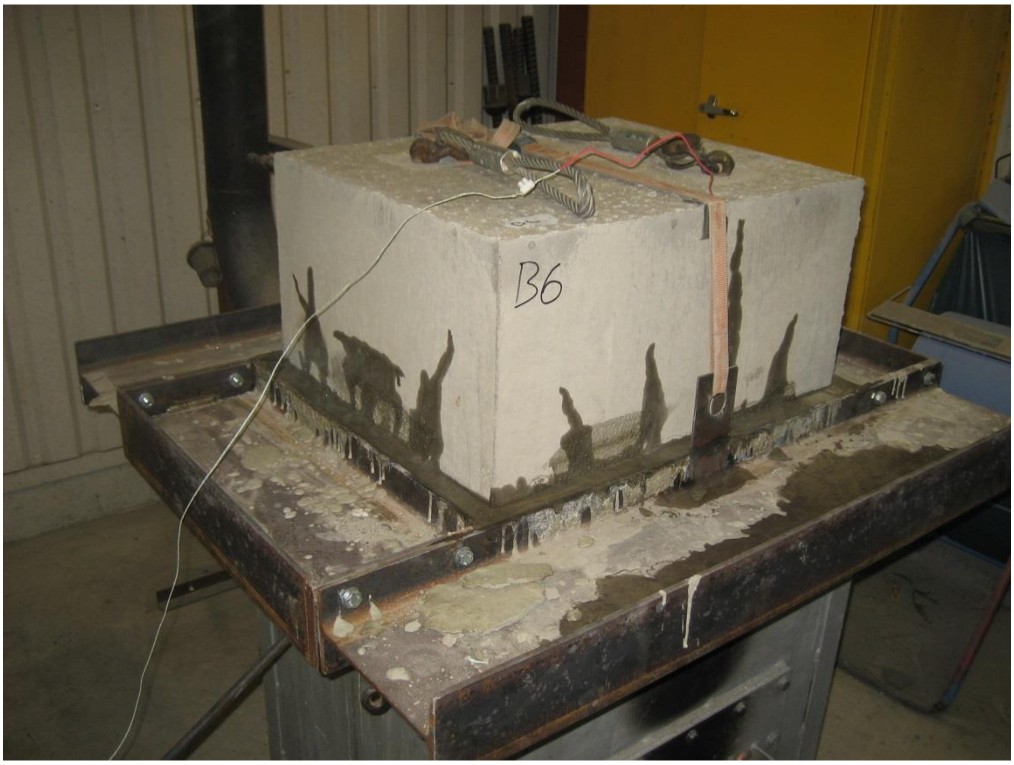

Figure A43. Test specimen during the test.

Figure A44. Test specimen after the test.

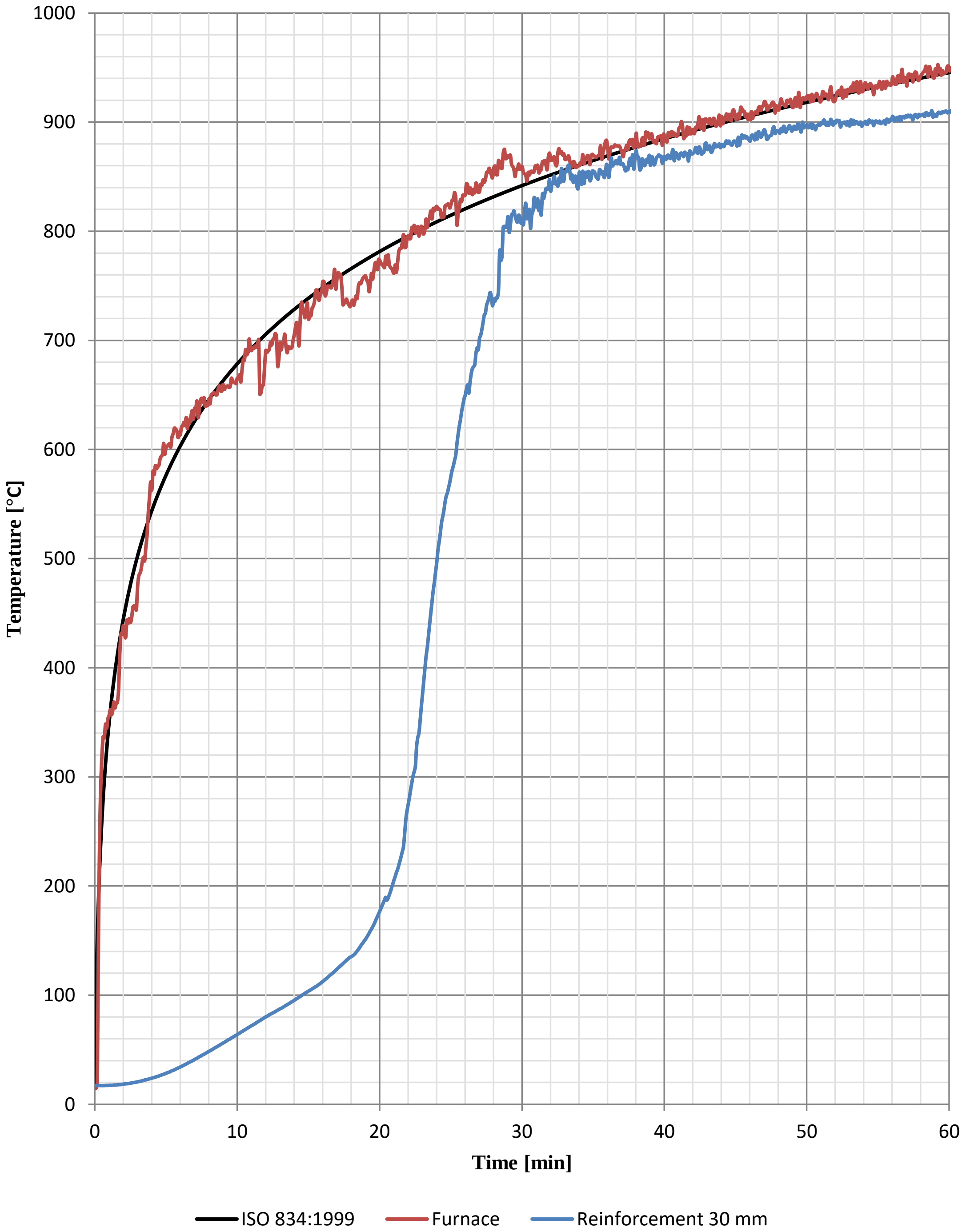

Figure A45. Measured temperatures during the test.

Small slab, restrained, 10: 500x600-400 Mix 3 0.40-0.0kgPP

The test was performed December 16, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
14:25	A loud bang is heard from the test specimen.
15:00	Small bangs are heard from the test specimen, continuous spalling.
20:00	Some water is visible on two vertical sides.
27:00	The spalling ends.
30:00	Water is visible on all vertical sides.
45:00	Water is visible on all vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
367.6*	353.0*	4.0*	46

*Including the weight of the frame used for restraining the test slab

Figure A46. Test specimen during the test.

Figure A47. Test specimen after the test.

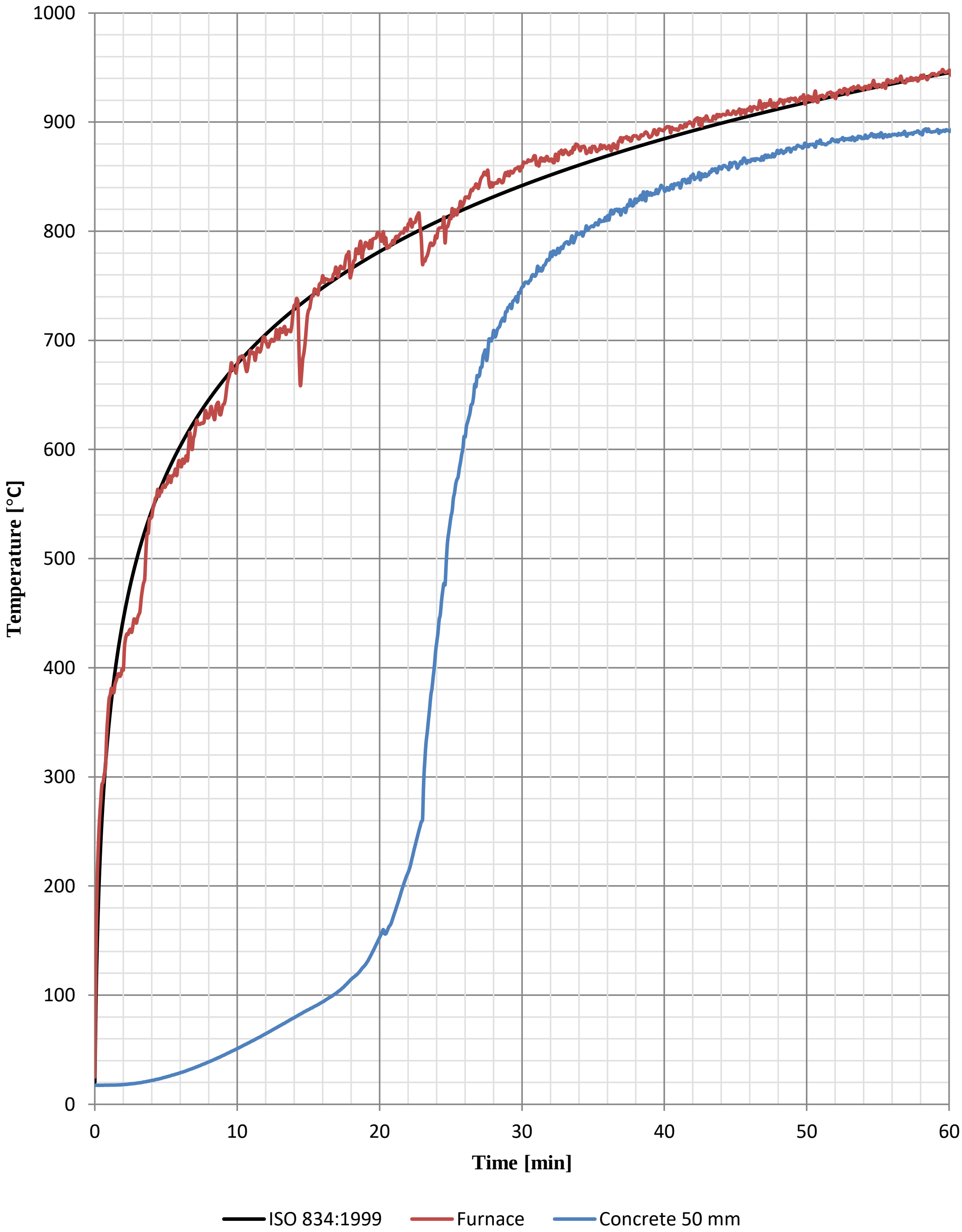

Figure A48. Measured temperatures during the test.

Small slab, restrained, 11: 500x600-400 Mix 3 0.40-0.0kgPP

The test was performed December 16, 2016.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
16:15	A loud bang is heard from the test specimen.
17:20	Small bangs are heard from the test specimen.
17:30	Small bangs are heard from the test specimen, continuous spalling.
20:00	Some water is visible on two vertical sides.
30:00	Some water is visible on all vertical sides.
31:00	The spalling ends.
32:25	A small bang is heard from the test specimen.
33:45	Two small bangs are heard from the test specimen.
45:00	Water is visible on all vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	Weight after [kg]	Weight reduction [%]	Maximum spalling depth [mm]
371.6	350.4	5.7	69

*Including the weight of the frame used for restraining the test slab

Figure A49. Test specimen during the test.

Figure A50. Test specimen after the test.

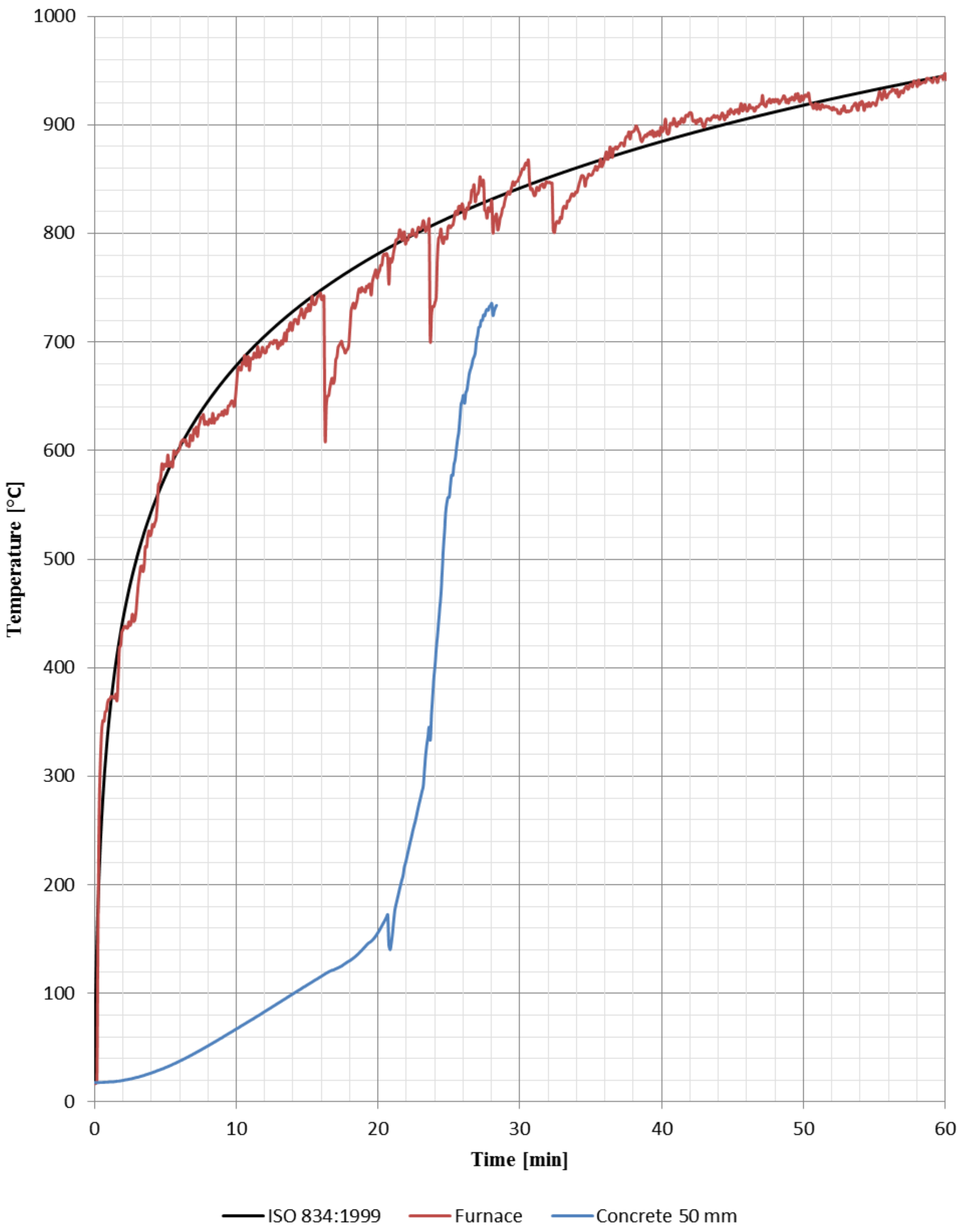

Figure A51. Measured temperatures during the test. The thermocouple Concrete 50 mm was out of order after 28,4 minutes of the test.

Small slab, restrained, 102: 500x600-400 Mix 3 0.40-0.0kgPP

The test was performed December 19, 2016.

Time [min:s]	**Observations** **(refer to the non-flame side if nothing else is stated)**
00:00	The test starts.
10:00	A bang is heard from the test specimen.
13:00	Two bangs are heard from the test specimen.
13:40	A small bang is heard from the test specimen.
13:55	A small bang is heard from the test specimen.
14:05	Small bangs are heard from the test specimen, continuous spalling.
25:00	A small amount of water is visible on three vertical sides.
30:00	Some water is visible on all vertical sides.
31:00	The spalling ends.
45:00	Water is visible on all vertical sides.
60:00	Water is visible on all vertical sides.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight before [kg]	**Weight after [kg]**	**Weight reduction [%]**	**Maximum spalling depth [mm]**
363.8	348.2	4.3	60

*Including the weight of the frame used for restraining the test slab

Figure A52. Test specimen during the test.

Figure A53. Test specimen after the test.

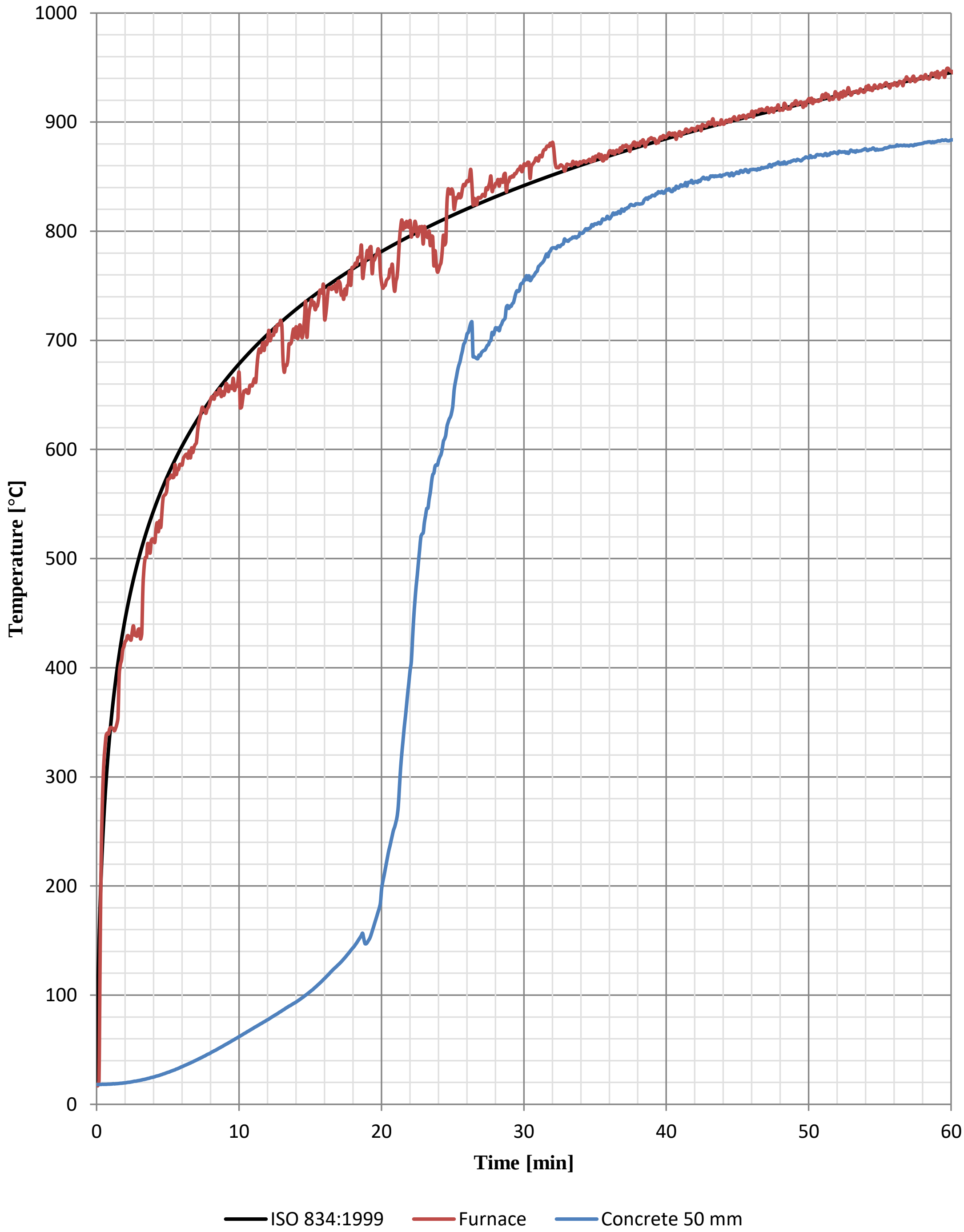

Figure A54. Measured temperatures during the test.

Large scale test: Wedge slabs, series no1

Test date: December 12, 2016

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
15:50	Wedge-Slab 21: 1000x500-50-300 Mix 2 0.33-0.0kgPP: Surface spalling at upper left corner.
17:20	Wedge-Slab 21: 1000x500-50-300 Mix 2 0.33-0.0kgPP: Further spalling at the upper region.
18:45	Wedge-Slab 21: 1000x500-50-300 Mix 2 0.33-0.0kgPP: Further spalling at the upper region, a bang is heard from the test specimen. The depth of the spalling at the upper edge is approximately 50 mm.
20:30	Wedge-Slab 21: 1000x500-50-300 Mix 2 0.33-0.0kgPP: Further spalling at the upper region.
21:20	Wedge-Slab 21: 1000x500-50-300 Mix 2 0.33-0.0kgPP: Some water is visible at the upper region.
60:00	The test terminates.

The spalling of the slabs were evaluated and sometimes measured after the test. Photographs describing each side of each slab are shown below. A number of maximum depths are shown in case of spalling.

Figure A55. Test specimen Wedge-Slab 25: 1000x500-50-300 Mix 1 0.33-1.0kgPP after the test.

Figure A56. Test specimen Wedge-Slab 25: 1000x500-50-300 Mix 1 0.33-1.0kgPP after the test.

Figure A57. Test specimen Wedge-Slab 26: 1000x500-50-300 Mix 1 0.33-1.0kgPP after the test.

Figure A58. Test specimen Wedge-Slab 26: 1000x500-50-300 Mix 1 0.33-1.0kgPP after the test.

Figure A59. Test specimen Wedge-Slab 27: 1000x500-50-300 Mix 1 0.33-1.0kgPP after the test.

Figure A60. Test specimen Wedge-Slab 27: 1000x500-50-300 Mix 1 0.33-1.0kgPP after the test.

Figure A61. Test specimen Wedge-Slab 19: 1000x500-50-300 Mix 2 0.33-0,0kgPP after the test. **Maximum spalling:** 22 mm

Figure A62. Test specimen Wedge-Slab 19: 1000x500-50-300 Mix 2 0.33-0,0kgPP after the test.

Figure A63. Test specimen Wedge-Slab 20: 1000x500-50-300 Mix 2 0.33-0.0kgPP after the test. **Maximum spalling:** 38 mm

Figure A64. Test specimen Wedge-Slab 20: 1000x500-50-300 Mix 2 0.33-0.0kgPP after the test. **Maximum spalling:** 34 mm

Figure A65. Test specimen Wedge-Slab 20: 1000x500-50-300 Mix 2 0.33-0.0kgPP after the test. **Side view.**

Figure A66. Test specimen Wedge-Slab 21: 1000x500-50-300 Mix 2 0.33-0.0kgPP after the test. **Maximum spalling:** 25 mm

Figure A67. Test specimen Wedge-Slab 21: 1000x500-50-300 Mix 2 0.33-0.0kgPP after the test.

Figure A68. Test specimen Wedge-Slab 22: 1000x500-50-300 Mix 3 0.40-0.0kgPP after the test.

Figure A69. Test specimen Wedge-Slab 22: 1000x500-50-300 Mix 3 0.40-0.0kgPP after the test.

Figure A70. Test specimen Wedge-Slab 23: 1000x500-50-300 Mix 3 0.40-0.0kgPP after the test. **Maximum spalling:** 32 mm

Figure A71. Test specimen Wedge-Slab 23: 1000x500-50-300 Mix 3 0.40-0.0kgPP after the test. **Maximum spalling:** 23 mm

Figure A72. Test specimen Wedge-Slab 24: 1000x500-50-300 Mix 3 0.40-0.0kgPP after the test.

Figure A73. Test specimen Wedge-Slab 24: 1000x500-50-300 Mix 3 0.40-0.0kgPP after the test. **Maximum spalling:** 42 mm

Figure A74. Test specimen Wedge-Slab 24: 1000x500-50-300 Mix 3 0.40-0.0kgPP after the test. Side view.

The temperature inside the concrete was measured with different amount of thermocouples in different test specimens. All thermocouples were placed in a centre line on the reinforcement net. The position is described in each temperature plot below. The specified dastans in the name of the measuring position is the distance from the lower edges of each test specimen.

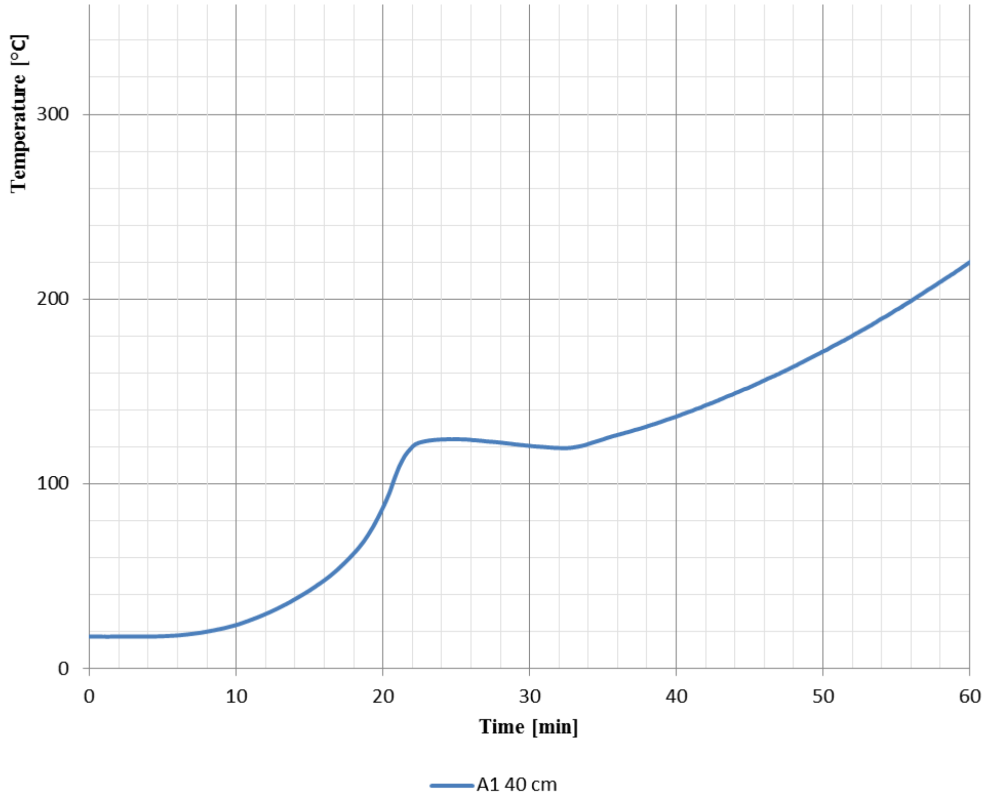

Figure A75. Temperature measurement in specimen Wedge-Slab 25: 1000x500-50-300 Mix 1 0.33-1.0kgPP

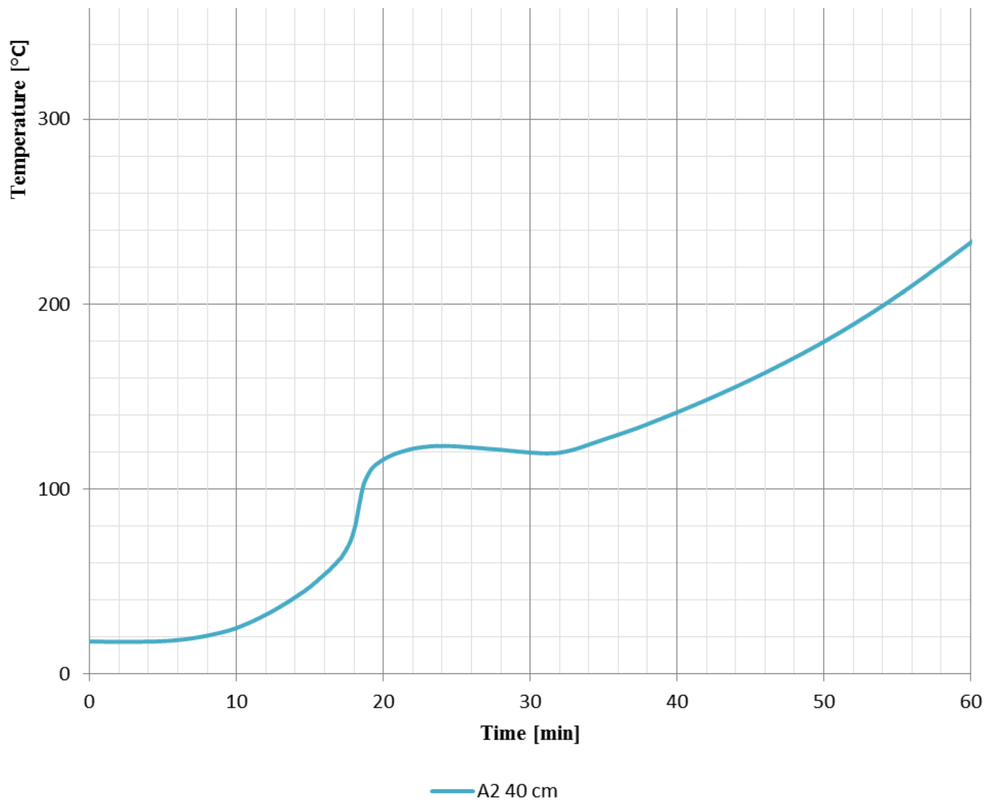

Figure A76. Temperature measurement in specimen Wedge-Slab 26: 1000x500-50-300 Mix 1 0.33-1.0kgPP

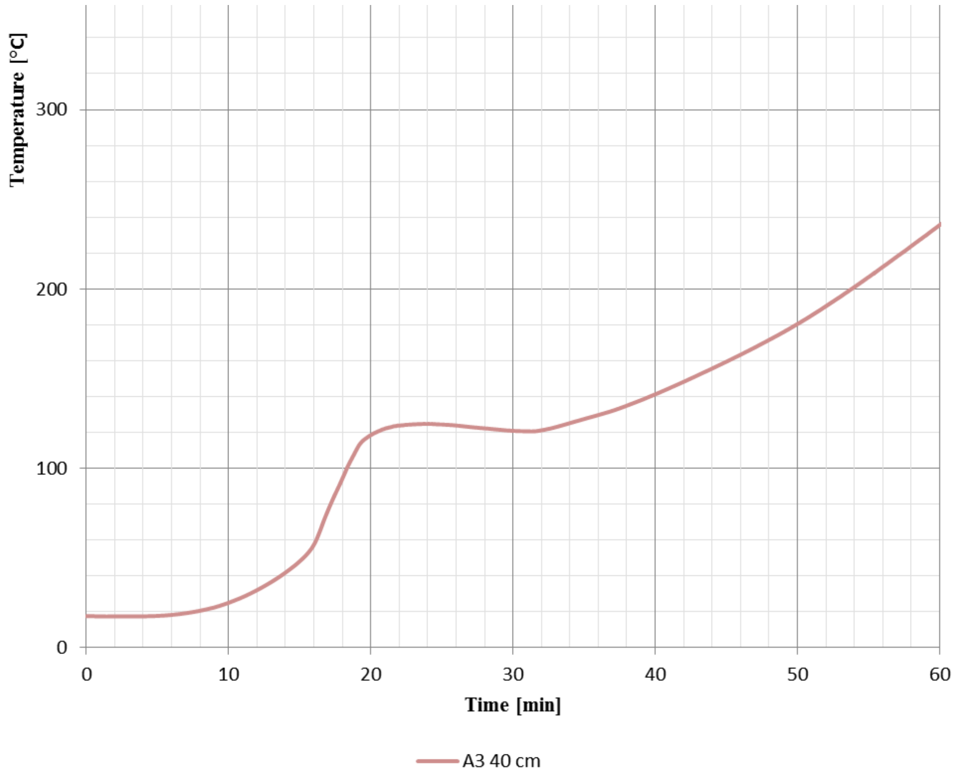

Figure A77. Temperature measurement in specimen Wedge-Slab 27: 1000x500-50-300 Mix 1 0.33-1.0kgPP

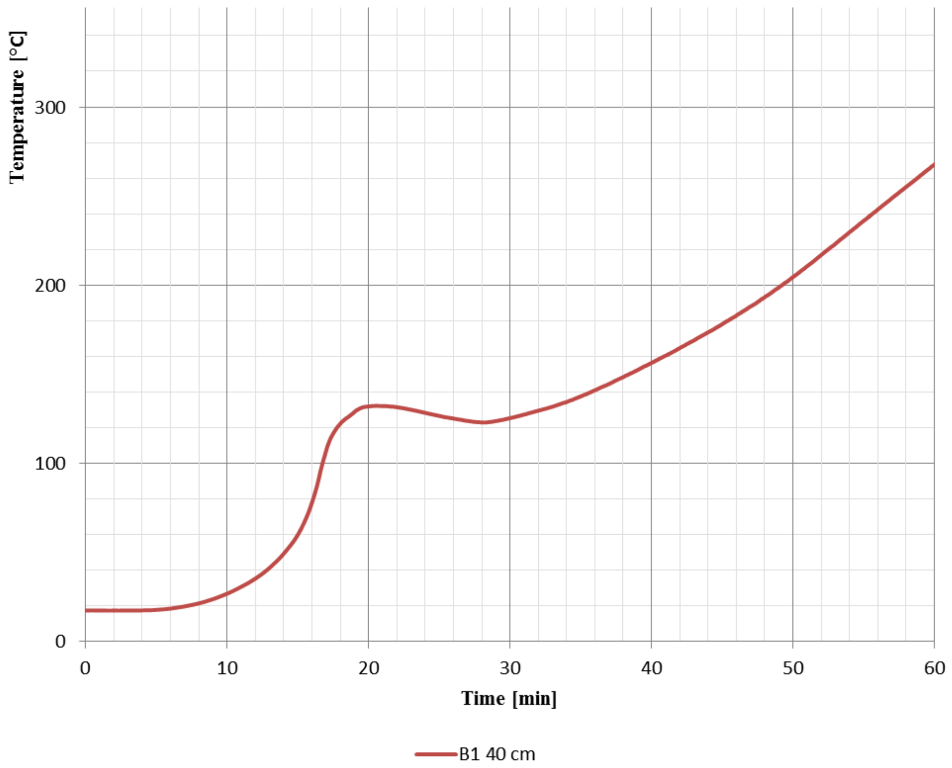

Figure A78. Temperature measurement in specimen Wedge-Slab 19: 1000x500-50-300 Mix 2 0.33-0.0kgPP

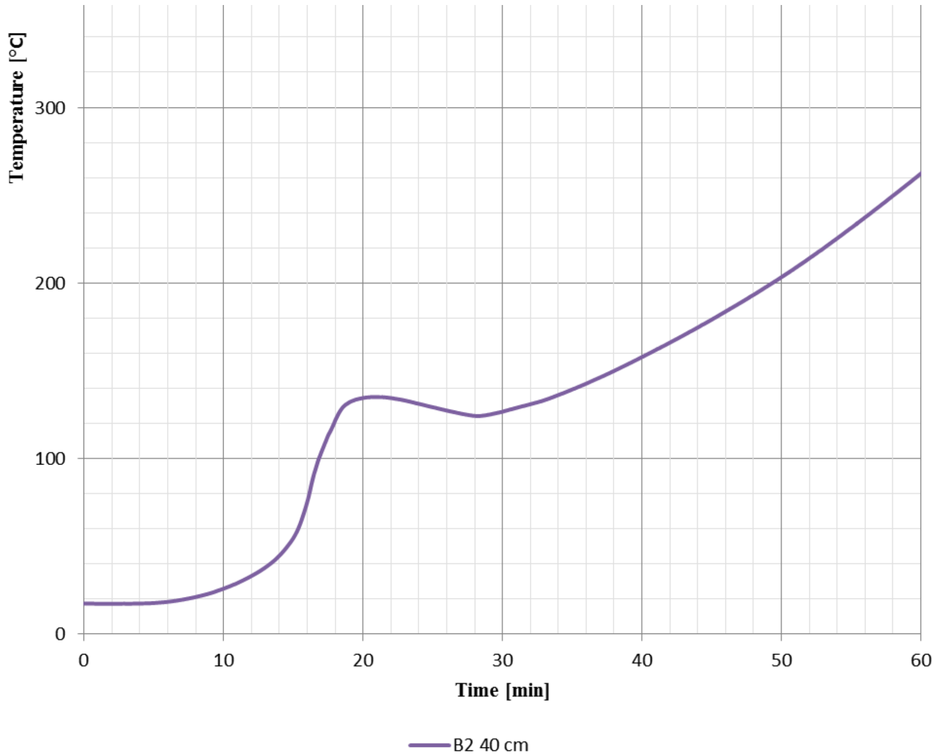

Figure A79. Temperature measurement in specimen Wedge-Slab 20: 1000x500-50-300 Mix 2 0.33-0.0kgPP

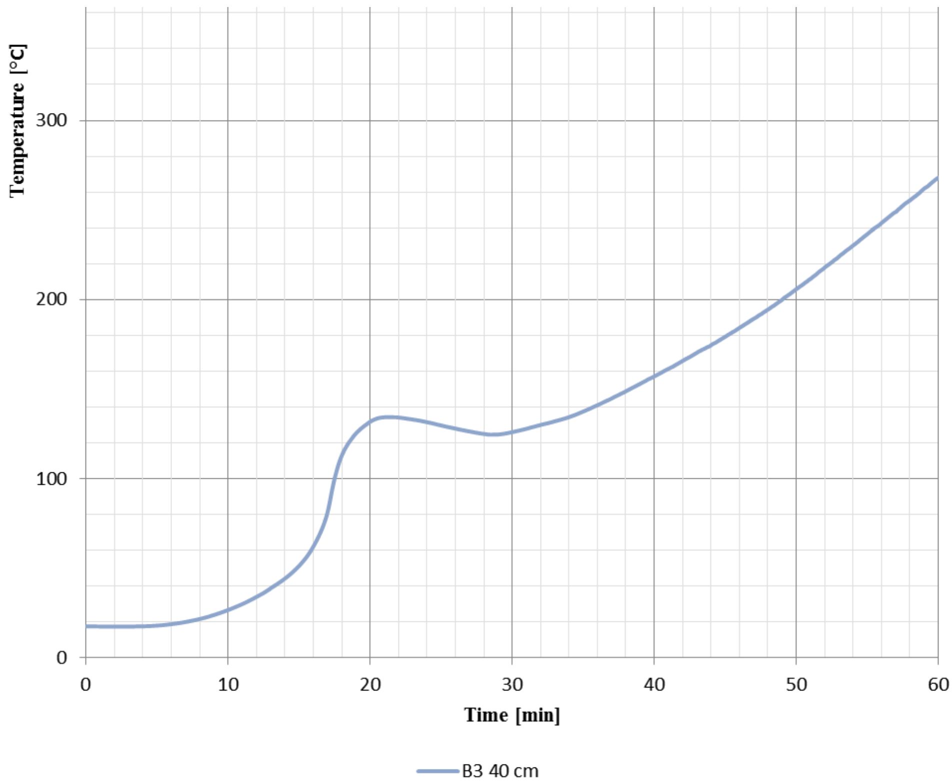

Figure A80. Temperature measurement in specimen Wedge-Slab 21: 1000x500-50-300 Mix 2 0.33-0.0kgPP

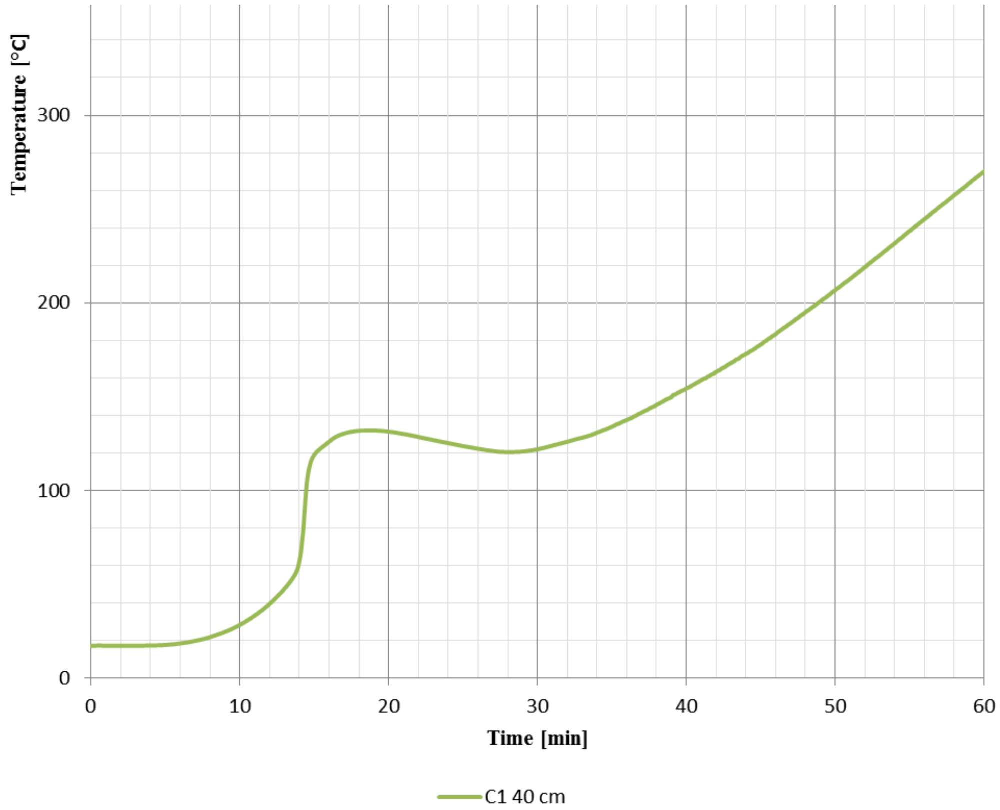

Figure A81. Temperature measurement in specimen Wedge-Slab 22: 1000x500-50-300 Mix 3 0.40-0.0kgPP

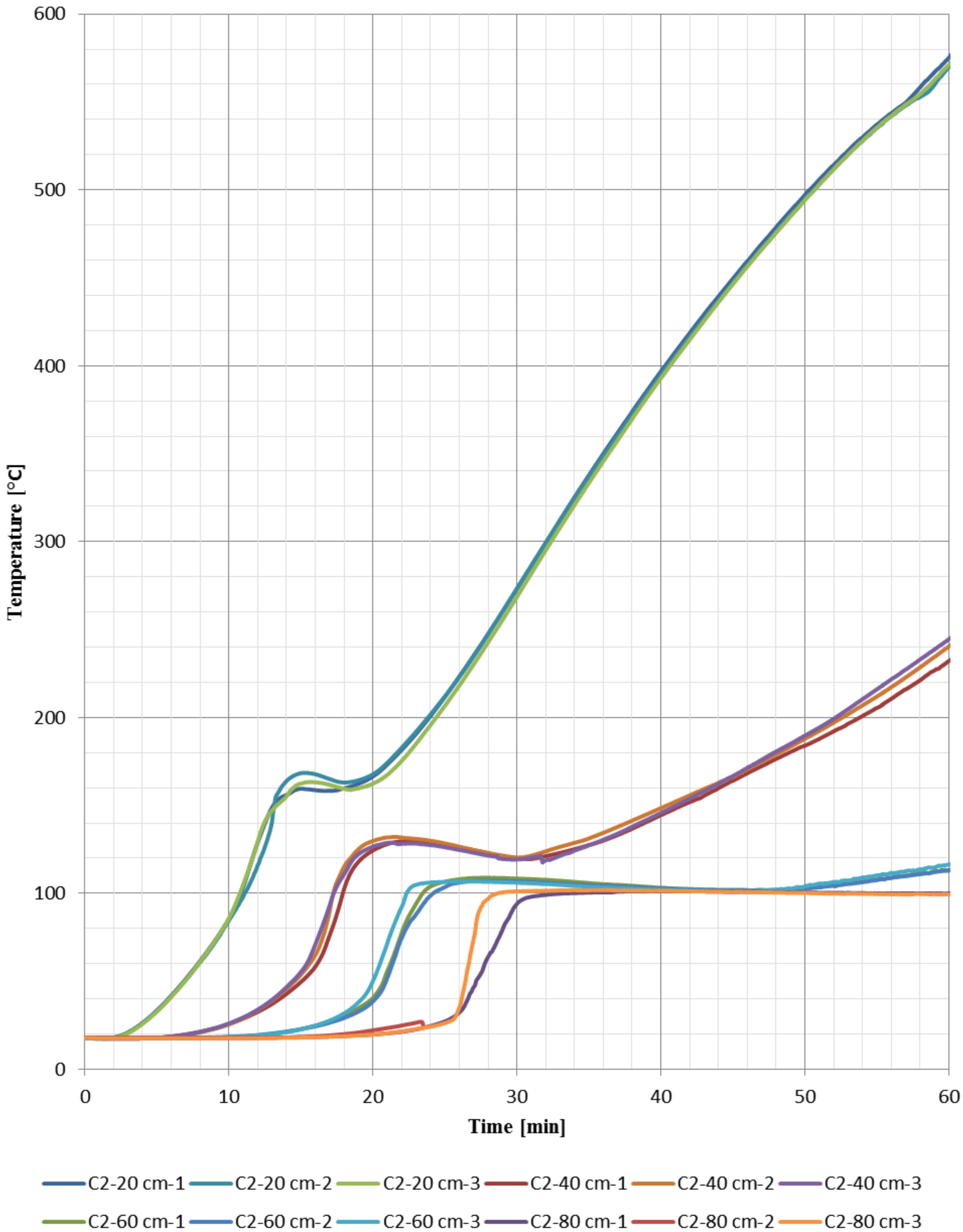

Figure A82. Temperature measurement in specimen Wedge-Slab 23: 1000x500-50-300 Mix 3 0.40-0.0kgPP

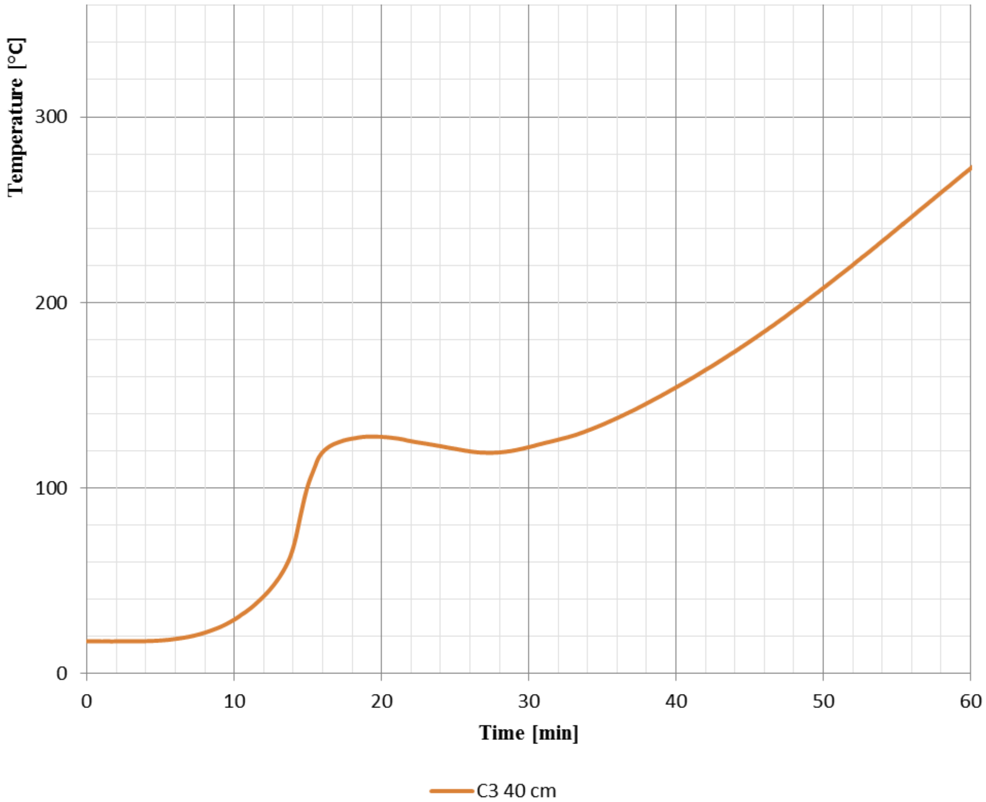

Figure A83. Temperature measurement in specimen Wedge-Slab 24: 1000x500-50-300 Mix 3 0.40-0.0kgPP

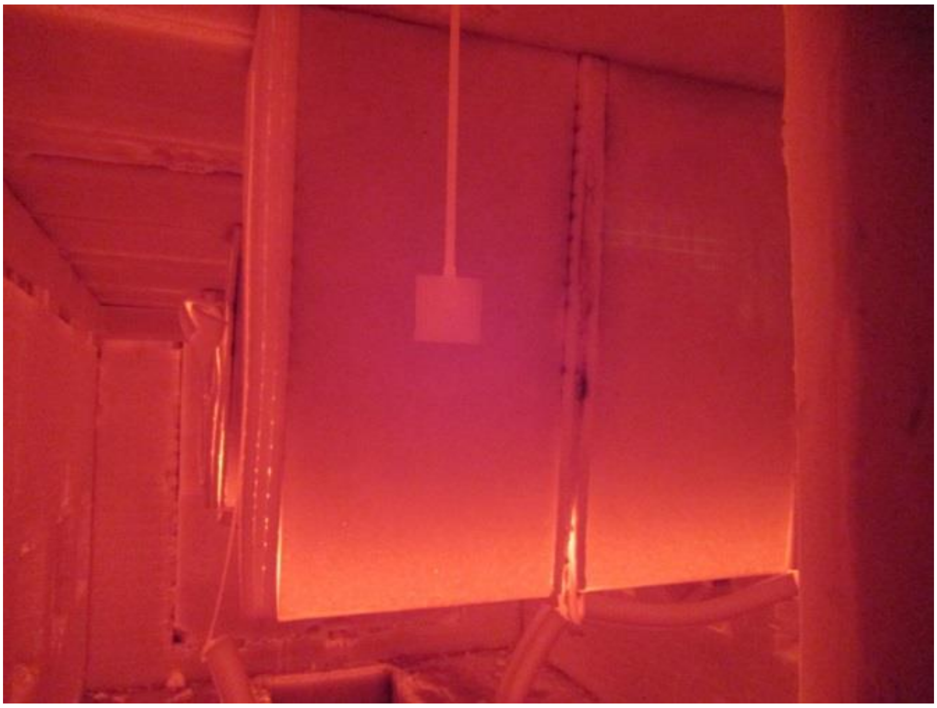

Figure A84. Test specimens Wedge-Slab 22: 1000x500-50-300 Mix 3 0.40-0.0kgPP, Wedge-Slab 19: 1000x500-50-300 Mix 2 0.33-0,0kgPP during the test.

Figure A85. Test specimen Wedge-Slab 21: 1000x500-50-300 Mix 2 0.33-0.0kgPP during the test.

The temperature in the furnace was controlled in accordance with EN 1363-1:2012. The pressure in the furnace was controlled to +20Pa 100 mm below the roof of the furnace.

The conditions in the furnace during the test are described below.

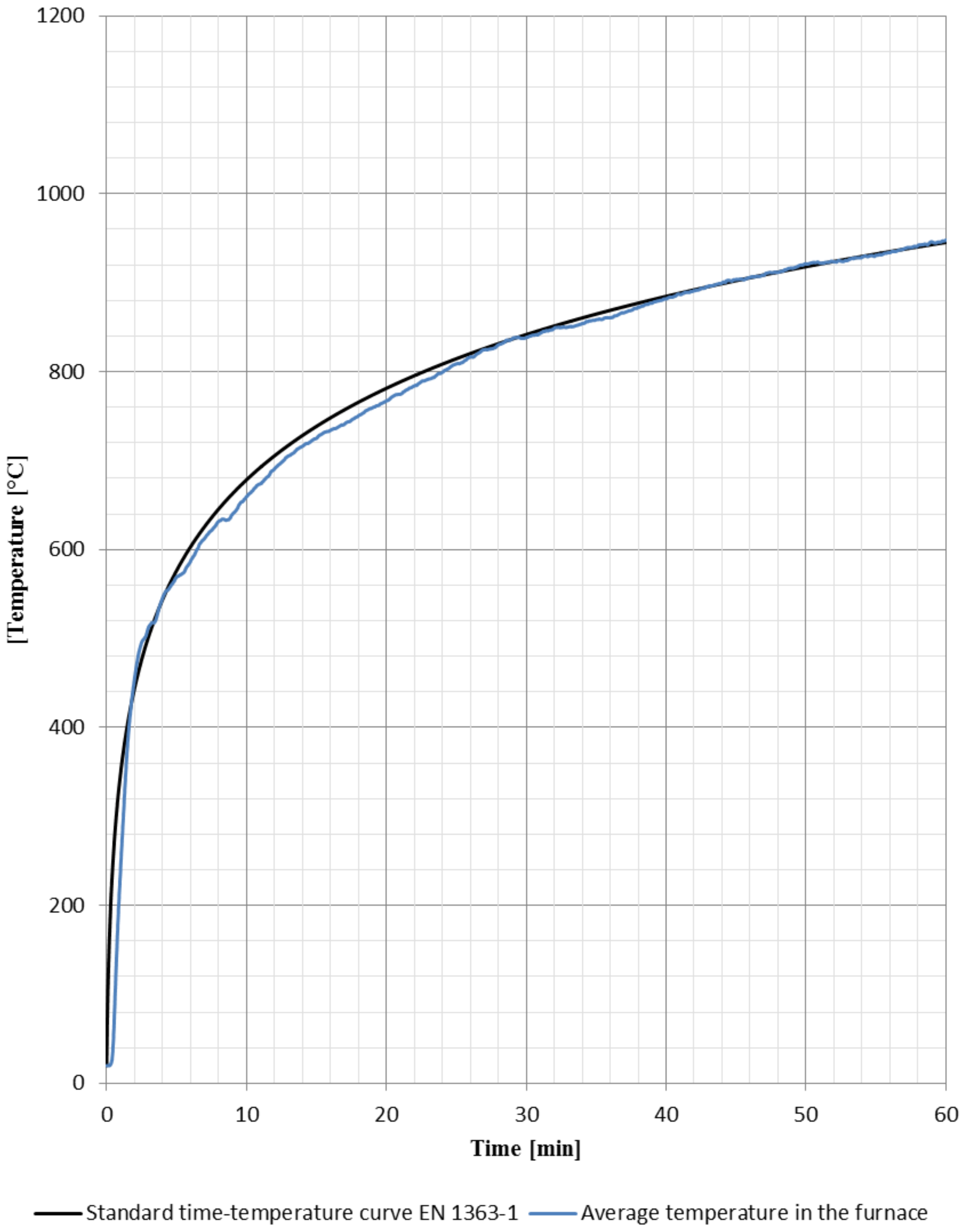

Figure A86. Average temperature in the furnace during the test.

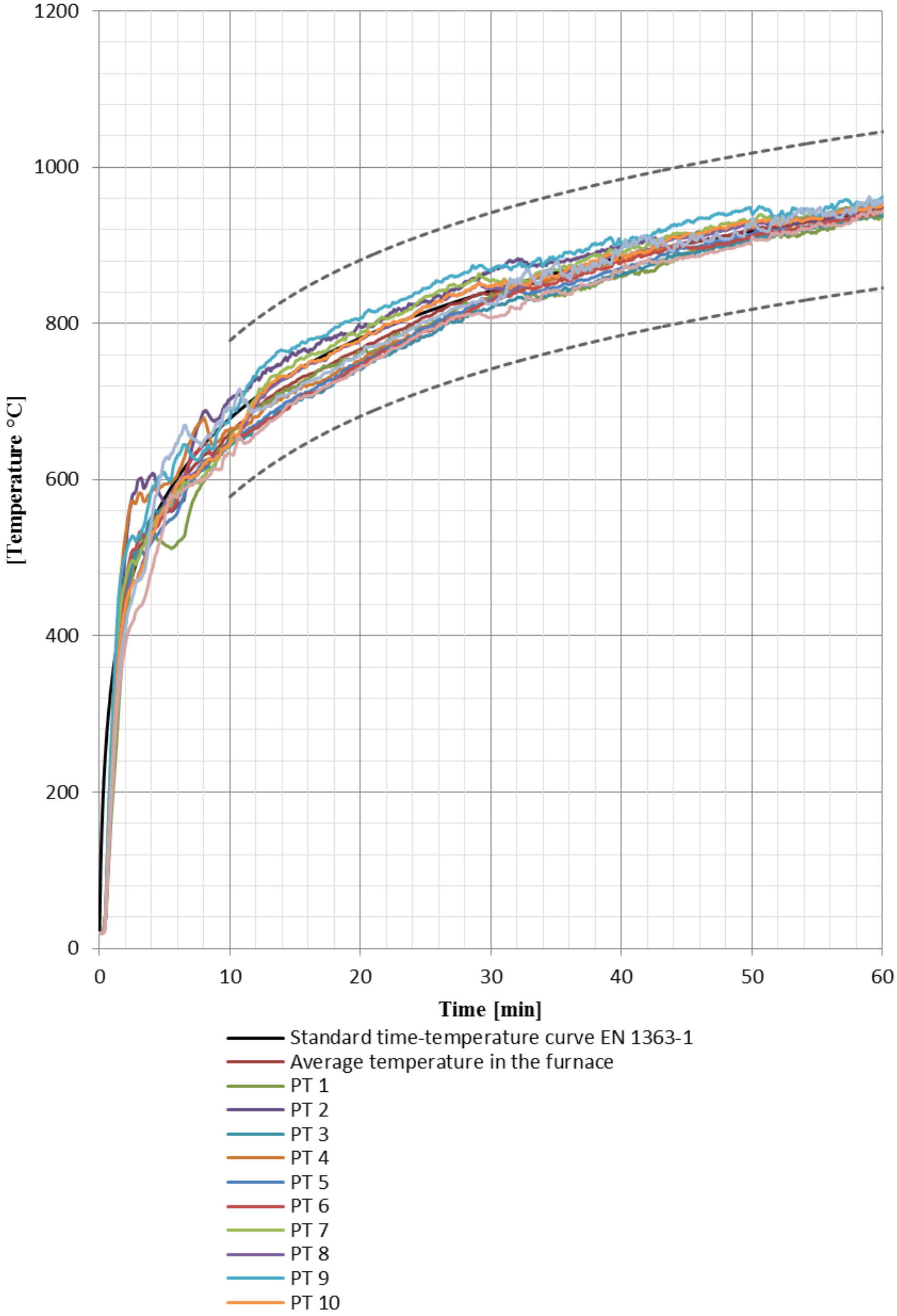

Figure A87. Measured temperatures in the furnace during the test.

Large scale test: Large scale slabs, series no 1

The test was performed December 15, 2016.

Time [min:s]	Observations (refer to the flame side if nothing else is stated)
00:00	The test starts.
01:15	Large slab 28: 4000x1670-600 Mix 2 0.33-0.0kg: The fire exposed surface starts spalling.
02:05	Large slab 28: 4000x1670-600 Mix 2 0.33-0.0kg: The main part of fire exposed surface has spalled off, the fire exposed surface along the edges are still unspalled.
02:20	Large slab 29: 4000x1670-600 Mix 3 0.40-0.0kg: The main part of the fire exposed surface spalls off.
02:30	Large slab 28: 4000x1670-600 Mix 2 0.33-0.0kg: Continuous spalling.
04:00	Large slab 28: 4000x1670-600 Mix 2 0.33-0.0kg: The whole fire exposed surface has spalled off. Large slab 29: 4000x1670-600 Mix 3 0.40-0.0kg: The whole fire exposed surface has spalled off.
09:20	Large slab 29: 4000x1670-600 Mix 3 0.40-0.0kg: Reinforcing bars are visible.
10:55	Large slab 29: 4000x1670-600 Mix 3 0.40-0.0kg: A longitudinal reinforcing bar is partly released from the concrete and is hanging down.
11:20	Large slab 29: 4000x1670-600 Mix 3 0.40-0.0kg: Two longitudinal reinforcing bars are visible.
11:35	Large slab 29: 4000x1670-600 Mix 3 0.40-0.0kg: Three longitudinal reinforcing bars are visible.
11:45	Large slab 29: 4000x1670-600 Mix 3 0.40-0.0kg: Transverse reinforcing bars are visible.
16:00	Large slab 28: 4000x1670-600 Mix 2 0.33-0.0kg:, Large slab 29: 4000x1670-600 Mix 3 0.40-0.0kg: The spalling frequency is reduced, only occasional spalling along the edges.
40:00	Large slab 29: 4000x1670-600 Mix 3 0.40-0.0kg: A spalled cavity is visible above the visible reinforcing bars.
61:00	The test terminates.

The spalling of the slabs was measured after the test. The measurements were made at positions of interest. The position of maximum spalling depth were also evaluated and measured.

The result from the measurement of spalling is described in the figures below.

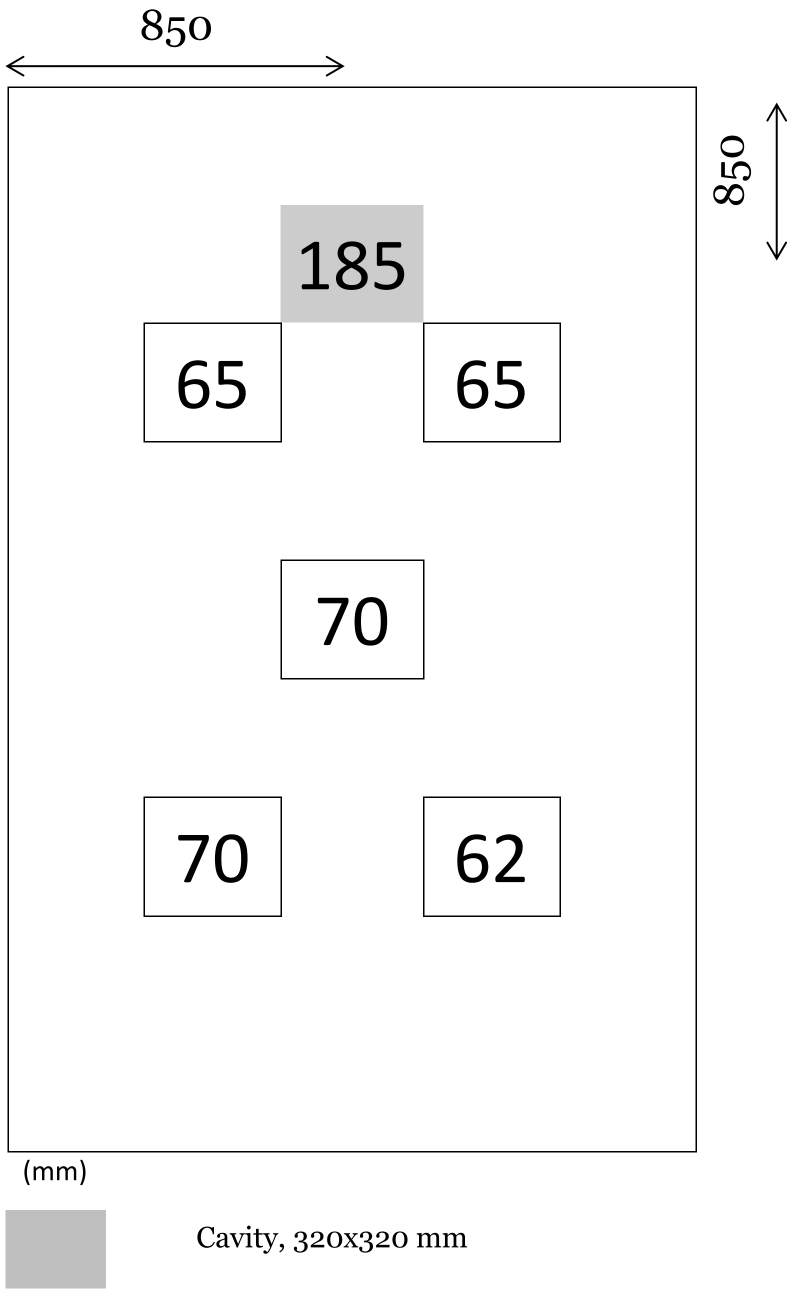

Figure A88. Spalling measurements on test specimen Large slab 29: 4000x1670-600 Mix 3 0.33-0.0kgPP. **Max spalling depth: 185 mm**

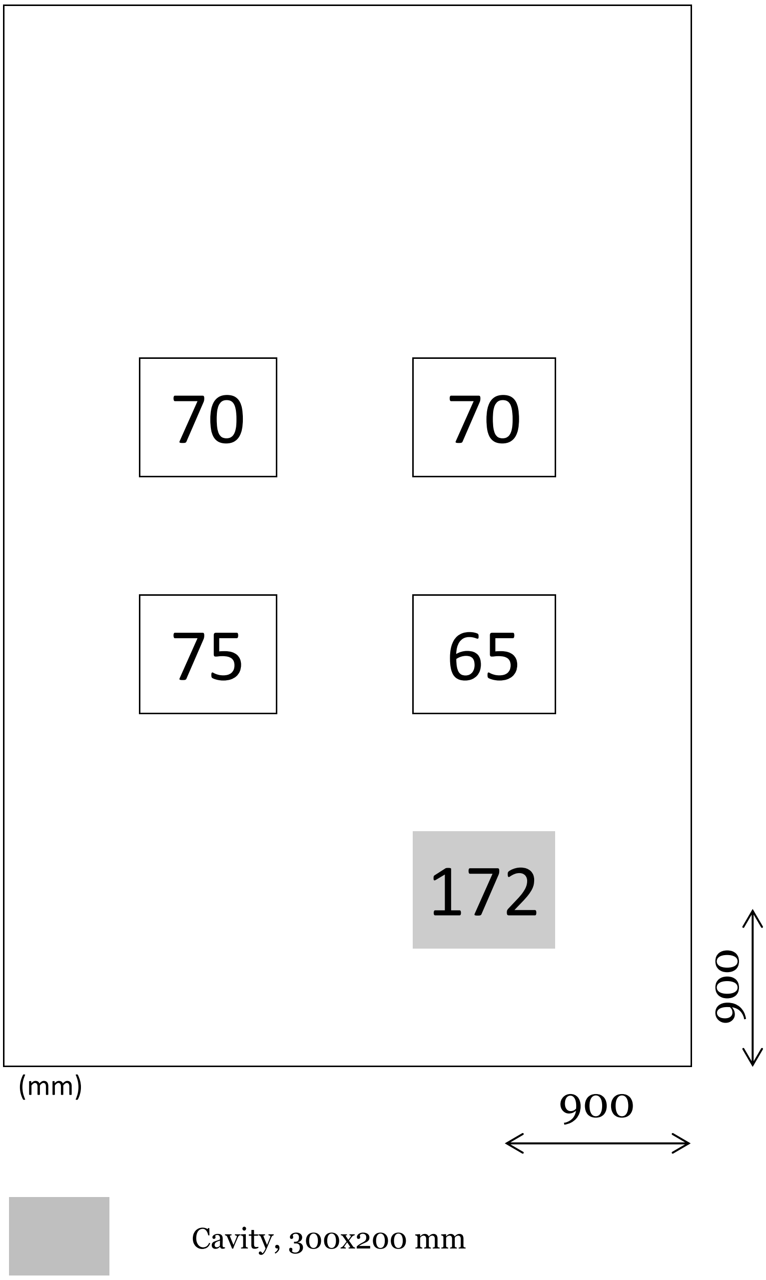

Figure A89. Spalling measurements on test specimen Large slab 28: 4000x1670-600 Mix 2 0.33-0.0kgPP. **Max spalling depth: 172 mm**

The temperature inside the concrete was measured with totally 12 thermocouples of each slab. The thermocouples were placed in two planes parallel to the fire exposed surface. One plane was paced 25 mm in to the concrete and the other was placed 16 mm both on to the reinforcement. Two thermocouples were placed at the fire exposed surface.

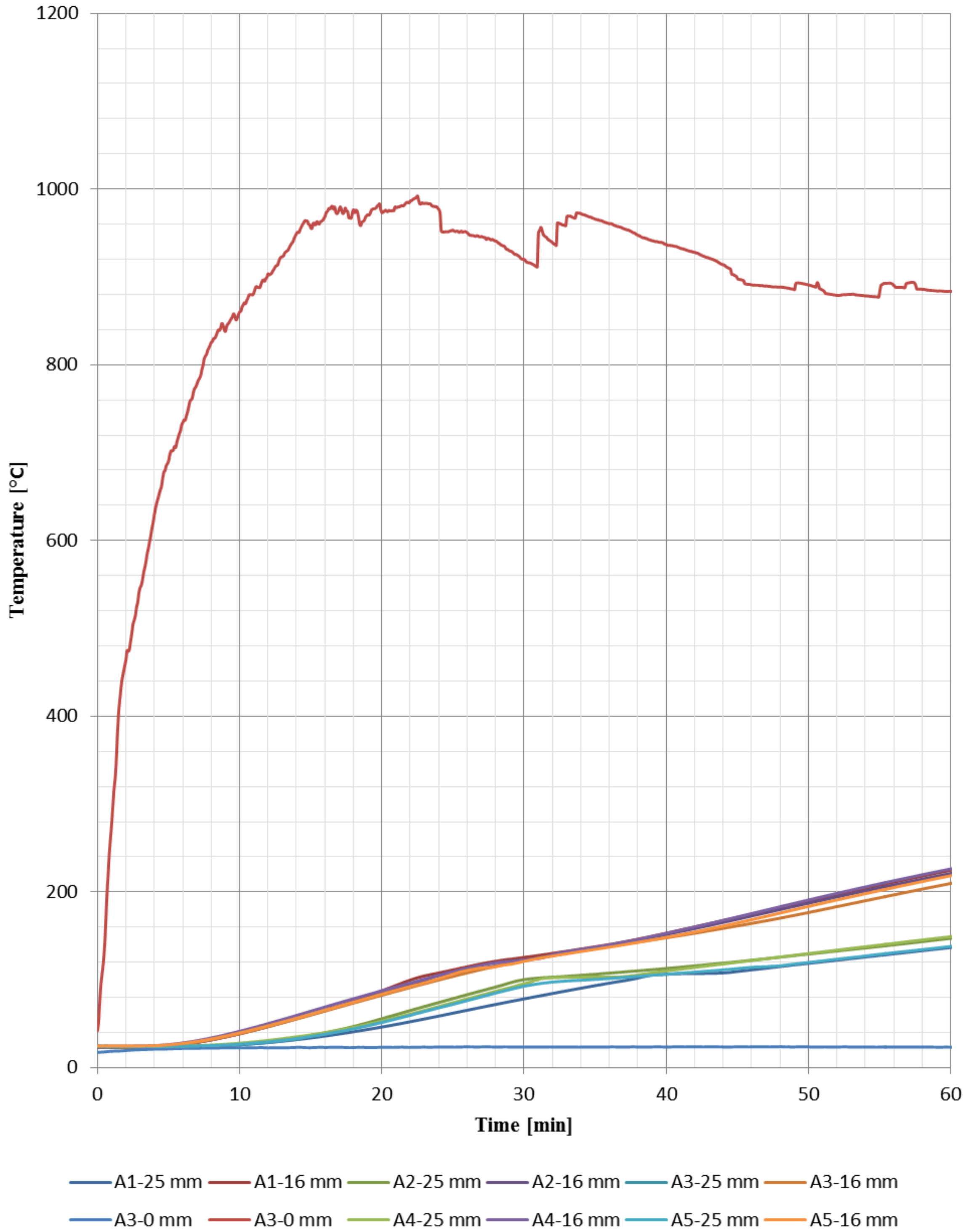

Figure A90. Temperature measurements in Large slab 30: 4000x1670-600 Mix 1 0,33-1,0kgPP. Thermocouple A3-25 mm was out of order after 14,3 minutes of the test

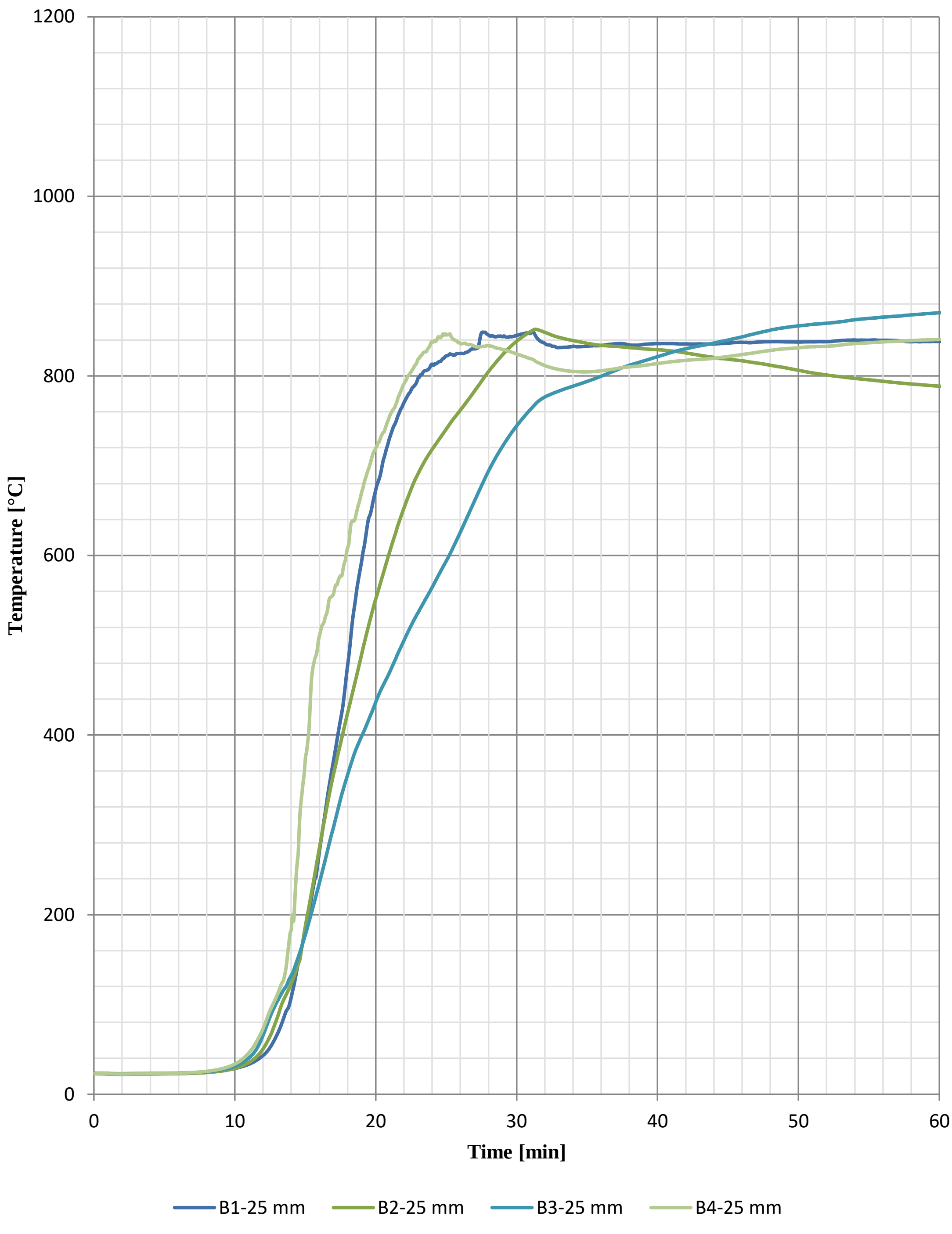

Figure A91. Temperature measurements in Large slab 28: 4000x1670-600 Mix 2 0.33-0,0kgPP. Note, thermocouples at 0 and 16 mm from the fire exposed surface were out of order during the test.

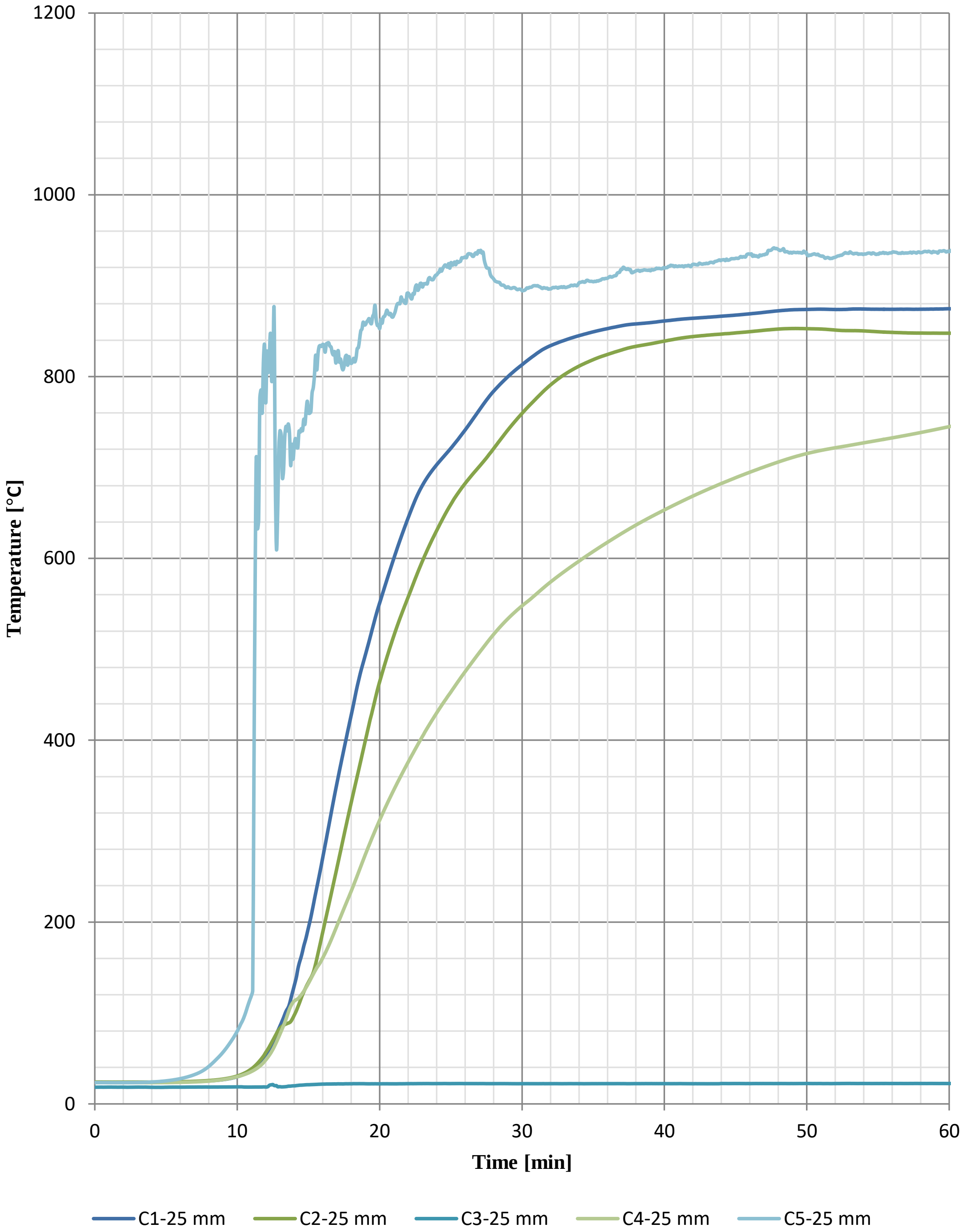

Figure A92. Temperature measurements in Large slab 29: 4000x1670-600 Mix 3 0,40-0,0kgPP. Note, thermocouples at 0 and 16 mm from the fire exposed surface were out of order during the test.

The climate in the furnace was controlled in accordance with EN 1363-1:2012 and the temperature was controlled in accordance with EN 1363-2:1999. Hydrocarbon curve was used. The pressure in the furnace was controlled to +20Pa 100 mm below the roof of the furnace.

The climate in the furnace during the test is described below.

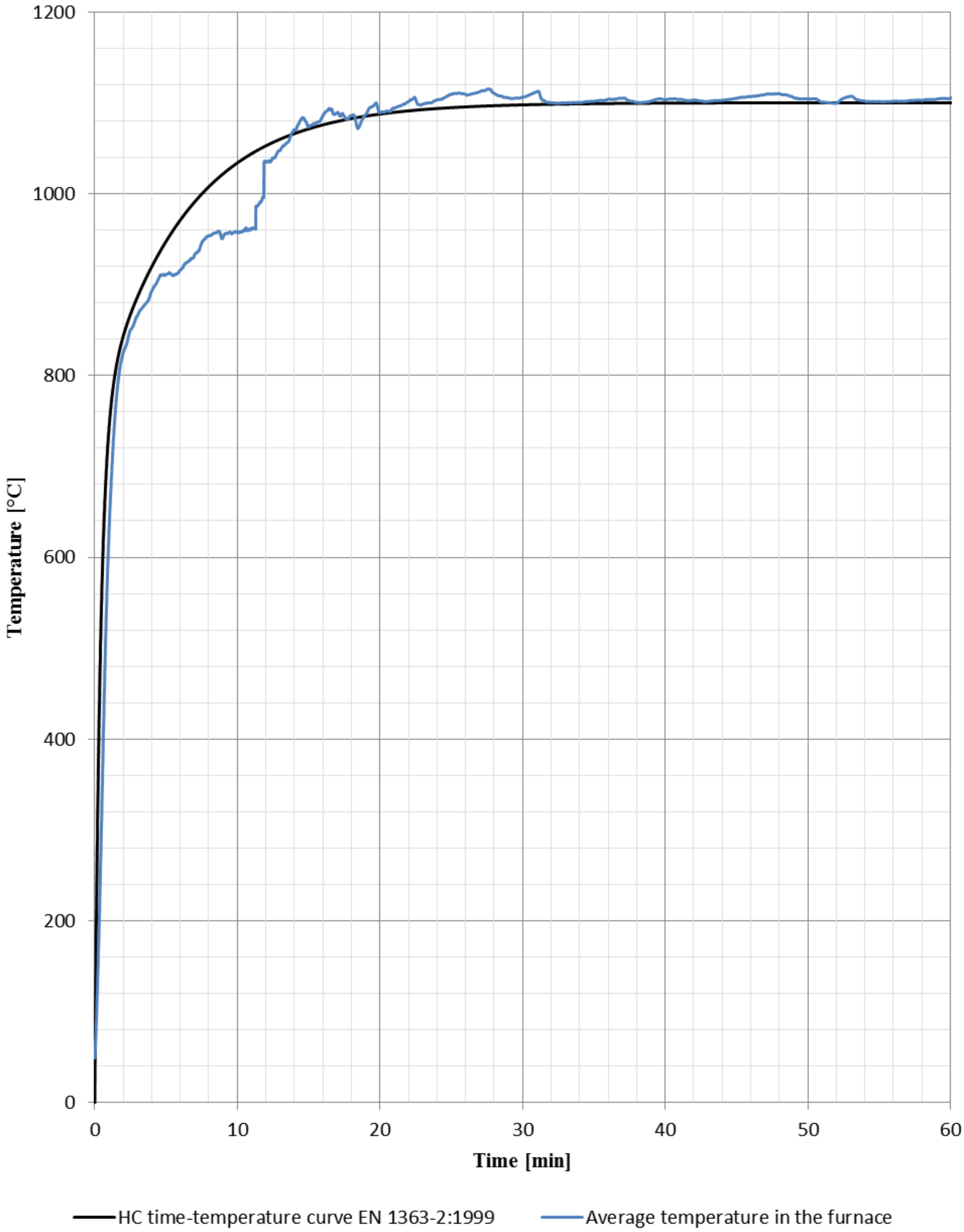

Figure A93. Average temperature in the furnace during the test. The furnace temperature was temporary cooled between 4 and 18 minutes of the test because high release of vapour during heavy spalling of the test specimen.

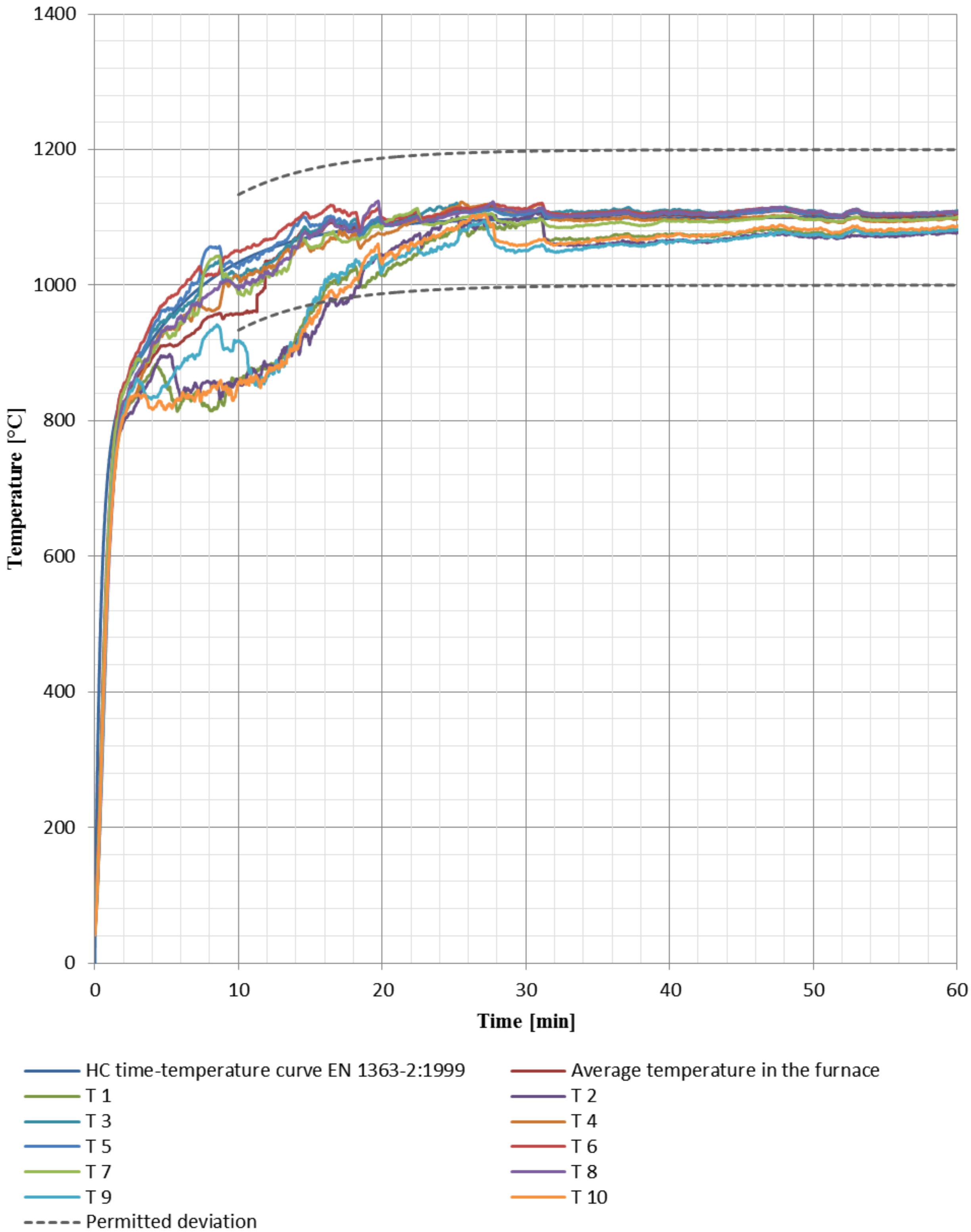

Figure A94. Measured temperatures in the furnace during the test. The furnace temperature was temporary cooled between 4 and 18 minutes of the test because high release of vapour during heavy spalling of the test specimen.

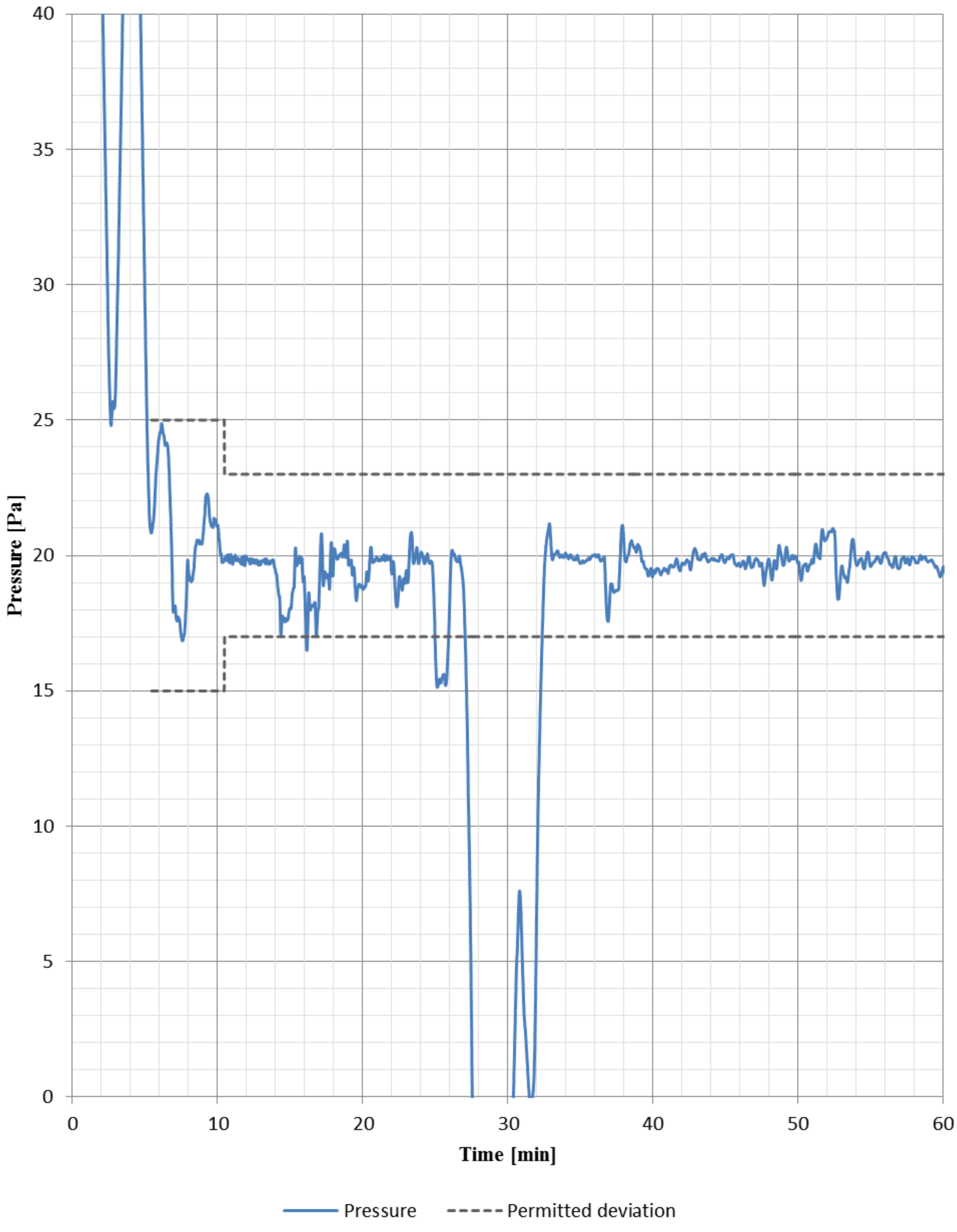

Figure A95. Measured pressure difference between the pressure in the furnace and the ambient pressure during the test. Note, the furnace pressure was lower than permitted during the period 24-32 minutes of the test. According to RISE´s experience this has no influence on the test results.

Figure A96. Test specimens on the furnace during the test.

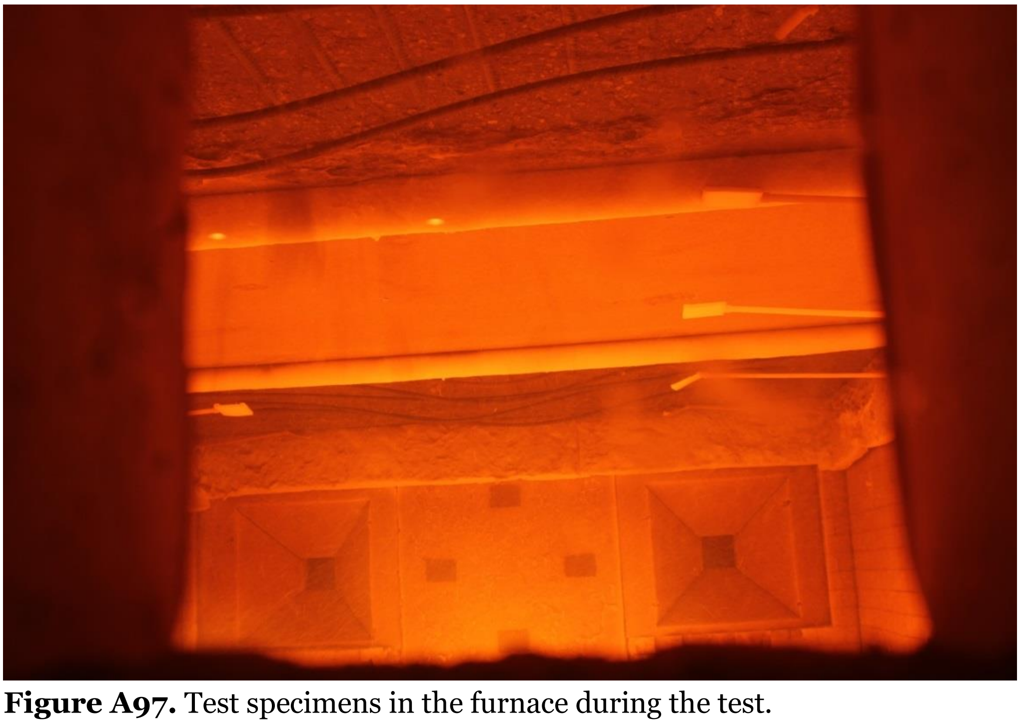

Figure A97. Test specimens in the furnace during the test.

Figure A98. Test specimen Large slab 28: 4000x1670-600 Mix 2 0.33-0,0kgPP after the test.

Figure A99. Test specimen Large slab 28: 4000x1670-600 Mix 2 0.33-0,0kgPP after the test.

Figure A100. Test specimen Large slab 28: 4000x1670-600 Mix 2 0.33-0,0kgPP after the test.

Figure A101. Test specimen Large slab 30: 4000x1670-600 Mix 1 0,40-1,0kgPP after the test.

Figure A102. Test specimen Large slab 30: 4000x1670-600 Mix 1 0,40-1,0kgPP after the test.

Figure A103. Test specimen Large slab 30: 4000x1670-600 Mix 1 0,40-1,0kgPP after the test.

Cylinders moulded in steel pipes, Gunma University type, series no 1

More information regarding these tests can be found in Jansson McNamee et al. (2017).

Mix[mix], [specimen number]	Maximum spalling [mm]	Start [min]	Stop [min]	Effective spalling time [min]
Mix1,1	0	0	0	0
Mix1,2	0	0	0	0
Mix2,1	40	18	32	14
Mix2,2	27	14	22	8
Mix3,1	0	0	0	0
Mix3,2	0	0	0	0

Figure A104. Test specimen MixB,1 after the fire test.

Unreinforced slabs, Cracow University type, series no 1

More information regarding these tests can be found in Jansson McNamee et al. (2017).

Mix[mix], [specimen number]	Maximum spalling [mm]	Start [min]	Stop [min]	Effective spalling time [min]
Mix3,1	31	12	27	15
Mix3,2	18	12	23	11

Figure A105. Test specimen Mix3,3 after the fire test.

Unreinforced slabs, Edinburgh University type, series no 1

More information regarding these tests can be found in Jansson McNamee et al. (2017).

Mix[mix], [specimen number]	Spalled area, first spall, [%]	Maximum spalling depth, first spall, [mm]	Spalling time (first spall), [min]
Mix3,1	20	9	6
Mix3,2	50	12	9
Mix3,3	38	13	7

Appendix B - Results series no 2

A summary of the test samples in test series No 2 is described in the table below.

Test method	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Series no 2						
Large slabs, vertical, loaded test				1	1	1
Small slabs (restrained)				2	2	2
Large ring specimens				3	3	3

Large ring specimens, test series no 2

Thermocouples

The temperature inside the concrete was measured with totally 2 thermocouples placed in two positions. One was paced 100 mm in to the concrete and the other was placed 50 mm into the concrete on to the reinforcement net from the fire exposed side.
One thermocouple was placed on the outer air side of the steel pipe. The thermocouple was placed near the connection to the furnace at one of the four positions were highest temperatures were expected.

Climate in the furnace

The test of the small scale slabs were performed in accordance with SP Brand 119. The fire exposure was in accordance with ISO 834.

Large ring specimen 1: Ø600-300-Mix 4-0.40-0.0kgPP

The test was performed August 14, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts
11:00	A bang is heard from the test specimen.
11:50	A small bang is heard from the test specimen.
12:05	A small bang is heard from the test specimen.
12:55	A bang is heard from the test specimen.
13:30	Continuous spalling.
25:00	Some water is observed between the steel pipe and the concrete.
36:00	The spalling ends.
60:00	Water is observed on the concrete surface along the steel pipe edge.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	Amount of spalled concrete [%]	Maximum spalling depth [mm]
22.6	9.0	85

Figure A106. Test specimen during the test.

Figure A107. Test specimen after the test.

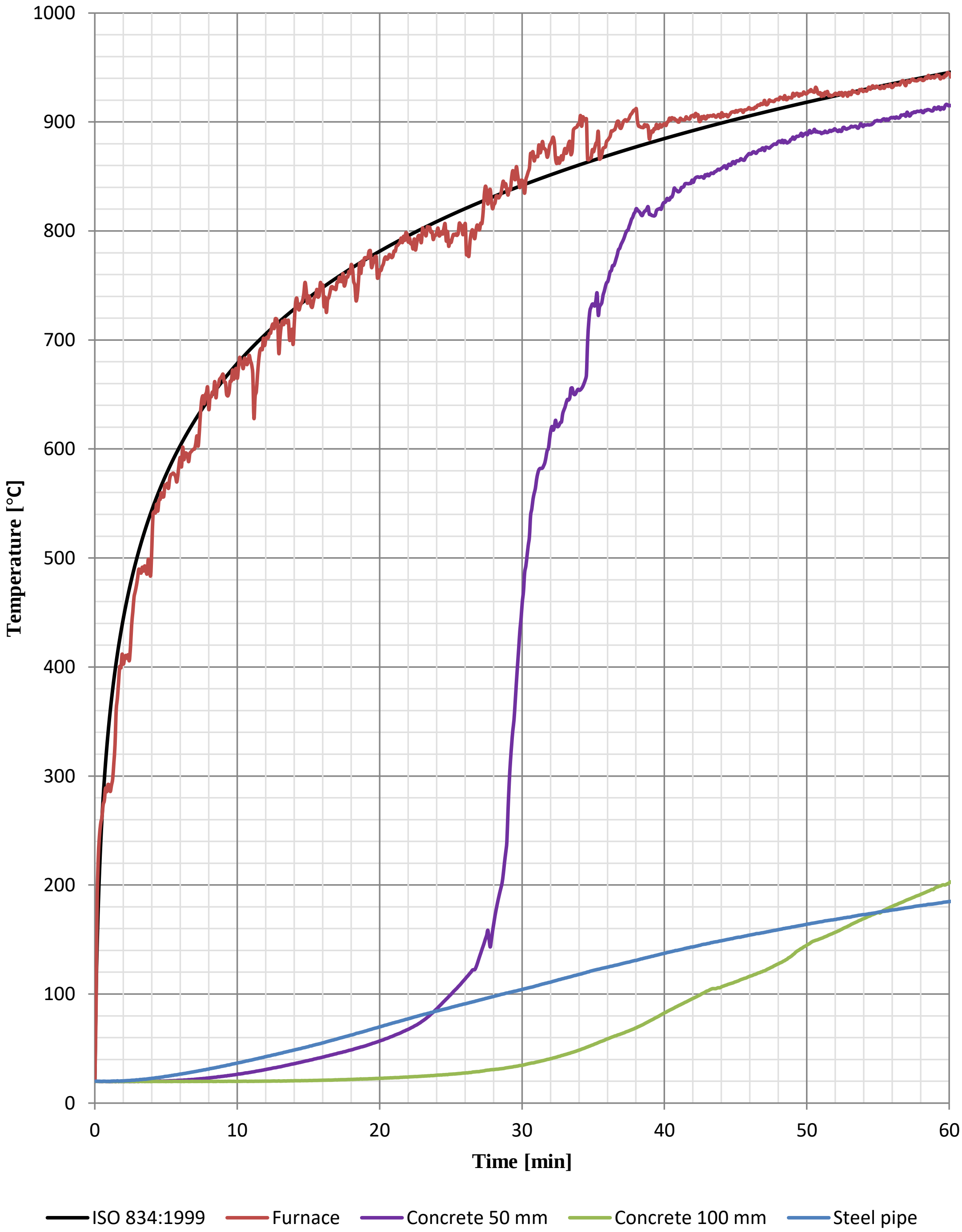

Figure A108. Temperature measurements during the test.

Large ring specimen 2: Ø600-300-Mix 4-0.40-0.0kgPP

The test was performed August 15, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts
09:00	A bang is heard from the test specimen.
10:00	A bang is heard from the test specimen.
10:40	A small bang is heard from the test specimen.
10:55	A bang is heard from the test specimen.
11:45	Continuous spalling.
35:00	The spalling ends. Water is observed on the concrete surface along the steel pipe edge.
60:00	A lot of water is observed on the upper concrete surface.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	Amount of spalled concrete [%]	Maximum spalling depth [mm]
20	7.9	73

Figure A109. Test specimen during the test.

Figure A110. Test specimen after the test.

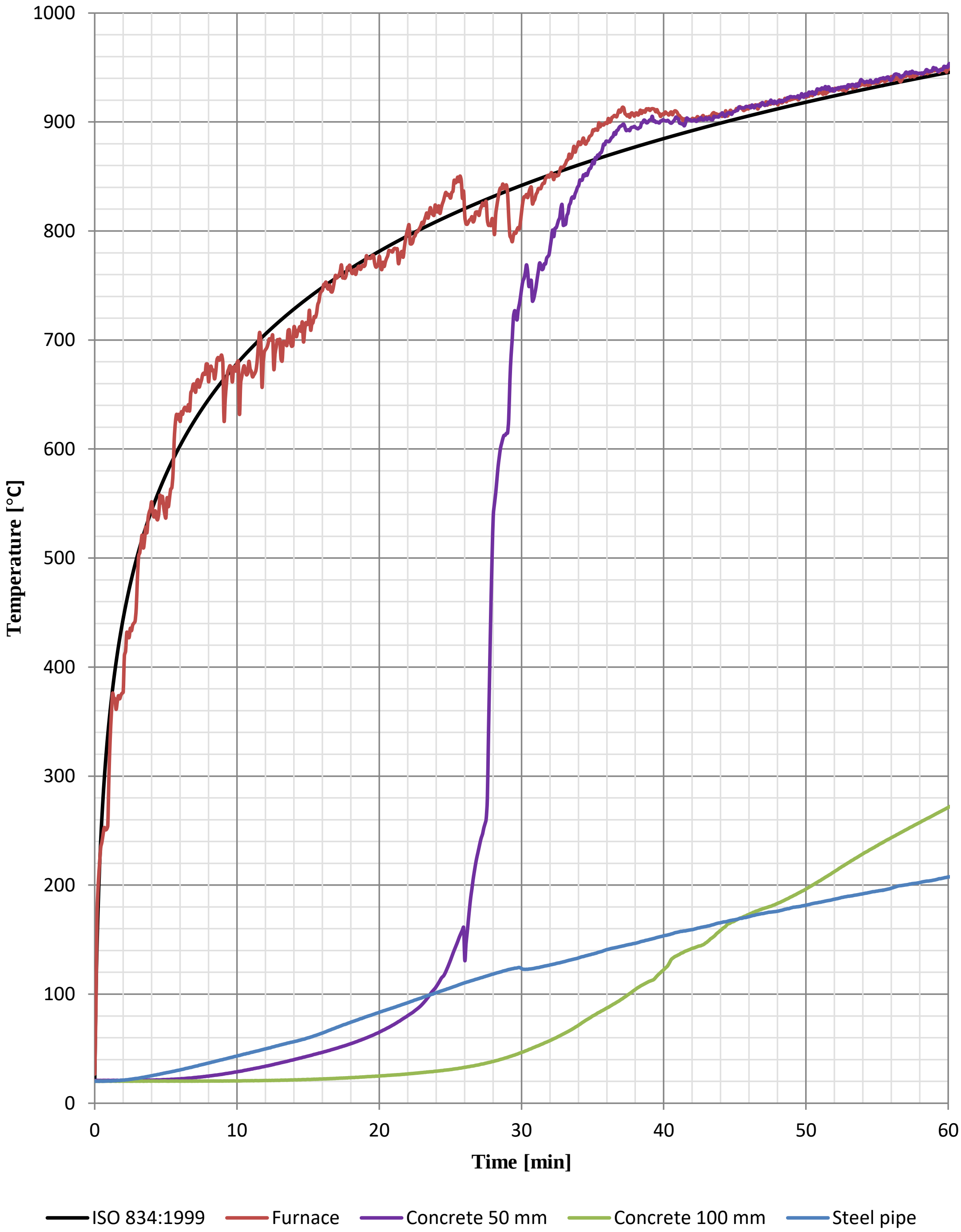

Figure A111. Temperature measurements during the test.

Large ring specimen 3: Ø600-300-Mix 4-0.40-0.0kgPP

The test was performed August 15, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts
09:00	A bang is heard from the test specimen.
10:50	Two bangs are heard from the test specimen.
11:20	A bang is heard from the test specimen.
12:35	A bang is heard from the test specimen.
13:10	Continuous spalling.
35:00	The spalling ends. Water is observed on the concrete surface along the steel pipe edge.
60:00	A lot of water is observed on the upper concrete surface.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	Amount of spalled concrete [%]	Maximum spalling depth [mm]
18.4	7.3	80

Figure A112. Test specimen during the test.

Figure A113. Test specimen after the test.

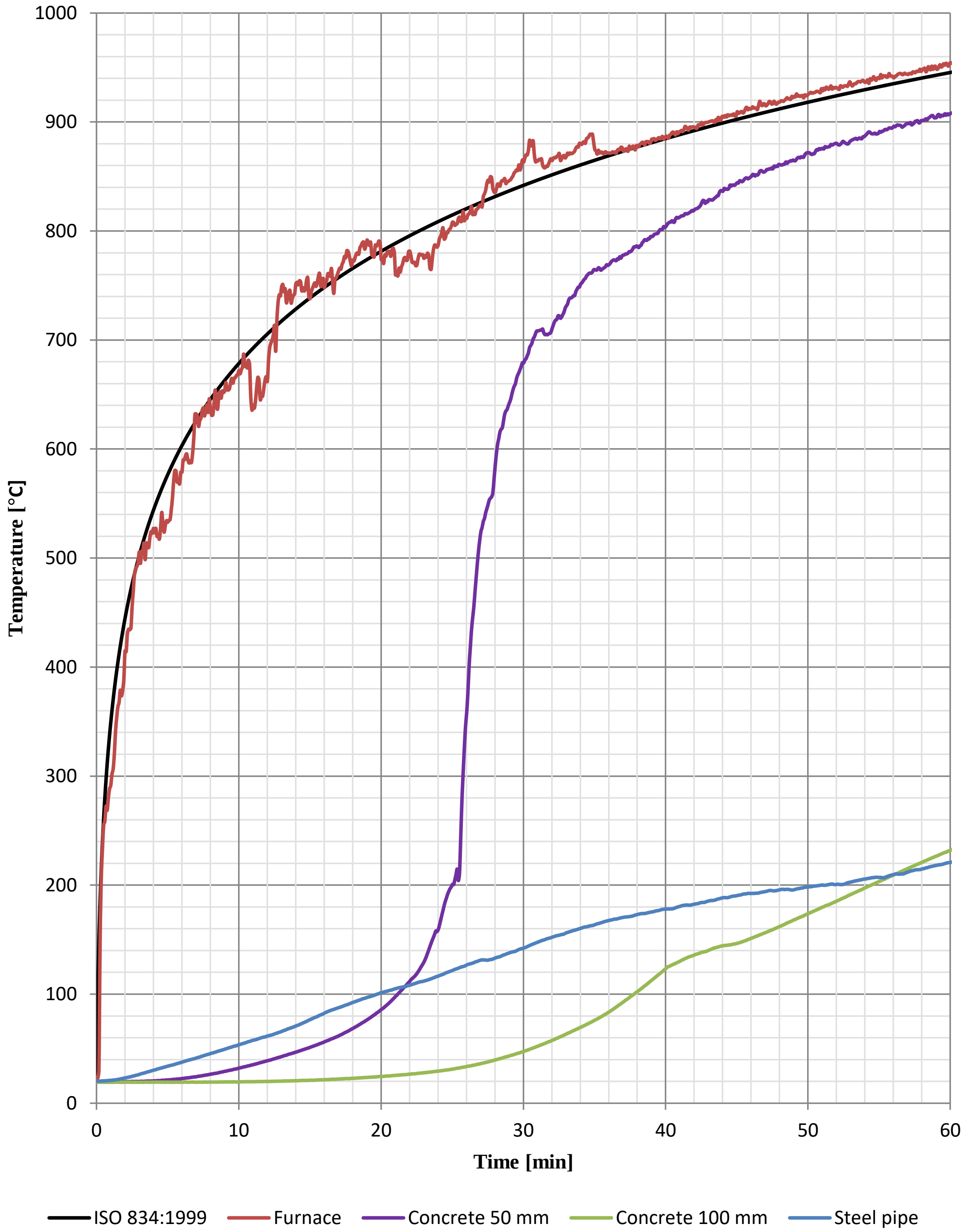

Figure A114. Temperature measurements during the test.

Large ring specimen 4: Ø600-300-Mix 5-0.40-0.2kgPP

The test was performed August 21, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts.
19:50	A big bang is heard from the test specimen.
21:20	A small bang is heard from the test specimen.
21:50	Continuous spalling.
32:00	The spalling ends.
38:00	Some water is observed on the top of the test specimen.
60:00	Water is observed on the top of the test specimen.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	Amount of spalled concrete [%]	Maximum spalling depth [mm]
-	-	62

Figure A115. Test specimen during the test.

Figure A116. Test specimen after the test.

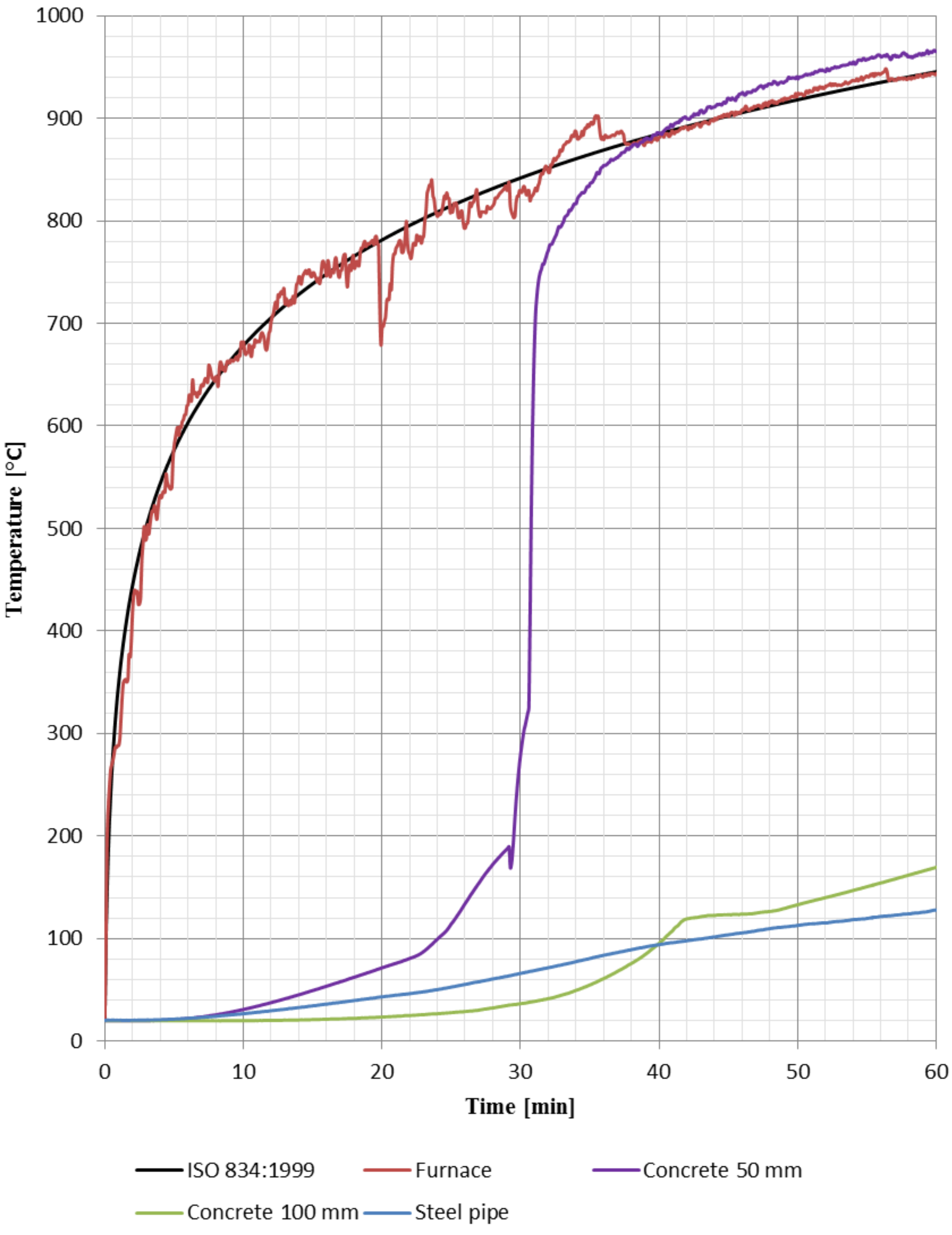

Figure A117. Temperature measurements during the test.

Large ring specimen 5 Ø600-300-Mix 5-0.40-0.2kgPP

The test was performed August 22, 2017.

Time [min:s]	**Observations (refer to the non-flame side if nothing else is stated)**
00:00	The test starts.
13:40	A small bang is heard from the test specimen.
16:10	A small bang is heard from the test specimen.
17:20	A big bang is heard from the test specimen.
18:00	A small bang is heard from the test specimen.
19:55	Continuous spalling.
31:00	The spalling ends.
40:00	Some water is observed on the top of the test specimen.
60:00	Water is observed on the top of the test specimen.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	**Amount of spalled concrete [%]**	**Maximum spalling depth [mm]**
14.6	5.8	52

Figure A118. Test specimen during the test.

Figure A119. Test specimen after the test.

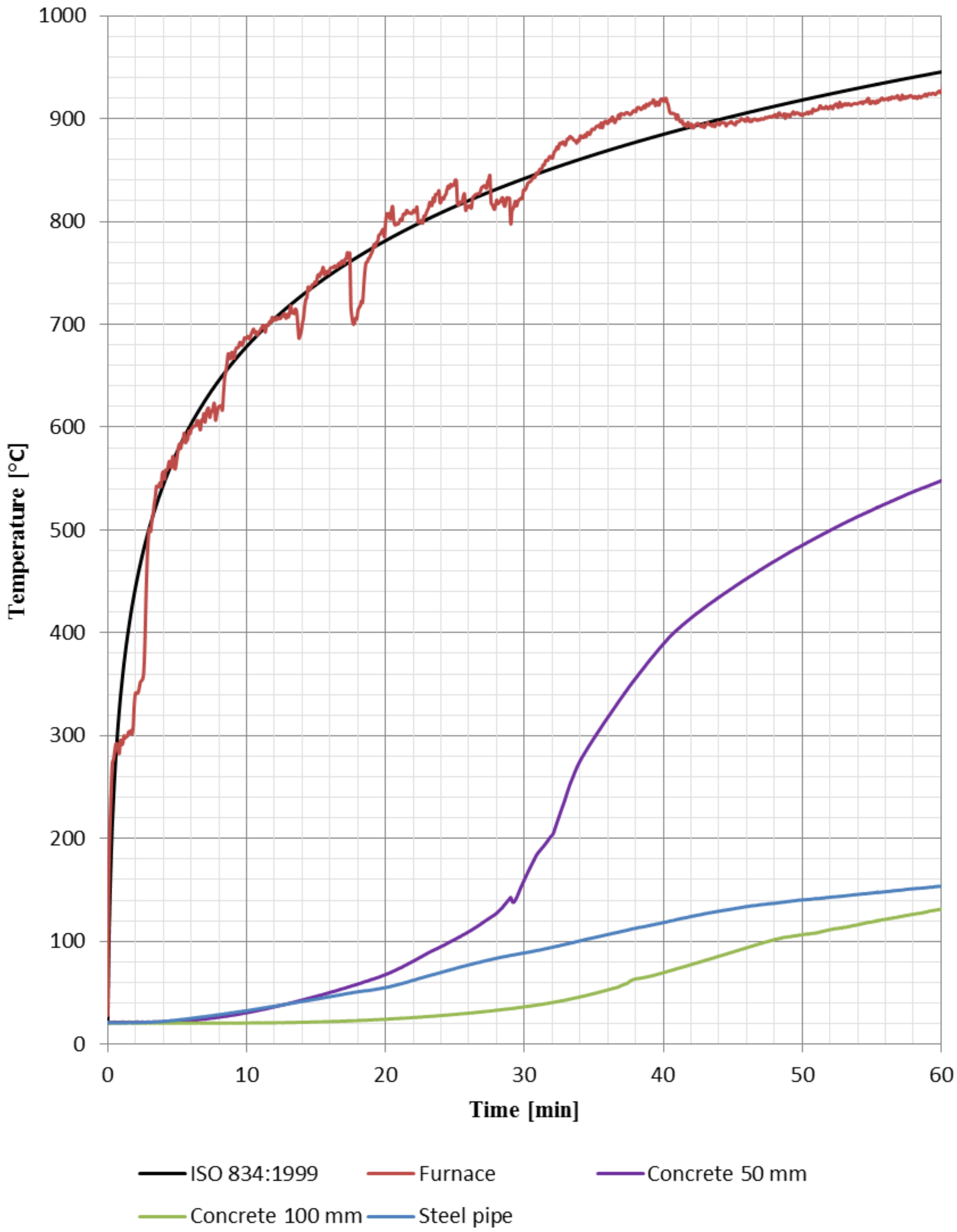

Figure A120. Temperature measurements during the test.

Large ring specimen 6: Ø600-300-Mix 5-0.40-0.2kgPP

The test was performed August 22, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts
22:55	A big bang is heard from the test specimen.
23:50	A small bang is heard from the test specimen.
24:05	A small bang is heard from the test specimen.
24:40	Continuous spalling.
35:00	The spalling ends. Some water is observed on the top of the test specimen.
60:00	Water is observed on the top of the test specimen.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	Amount of spalled concrete [%]	Maximum spalling depth [mm]
22.4	9.0	70

Figure A121. Test specimen during the test.

Figure A122. Test specimen after the test.

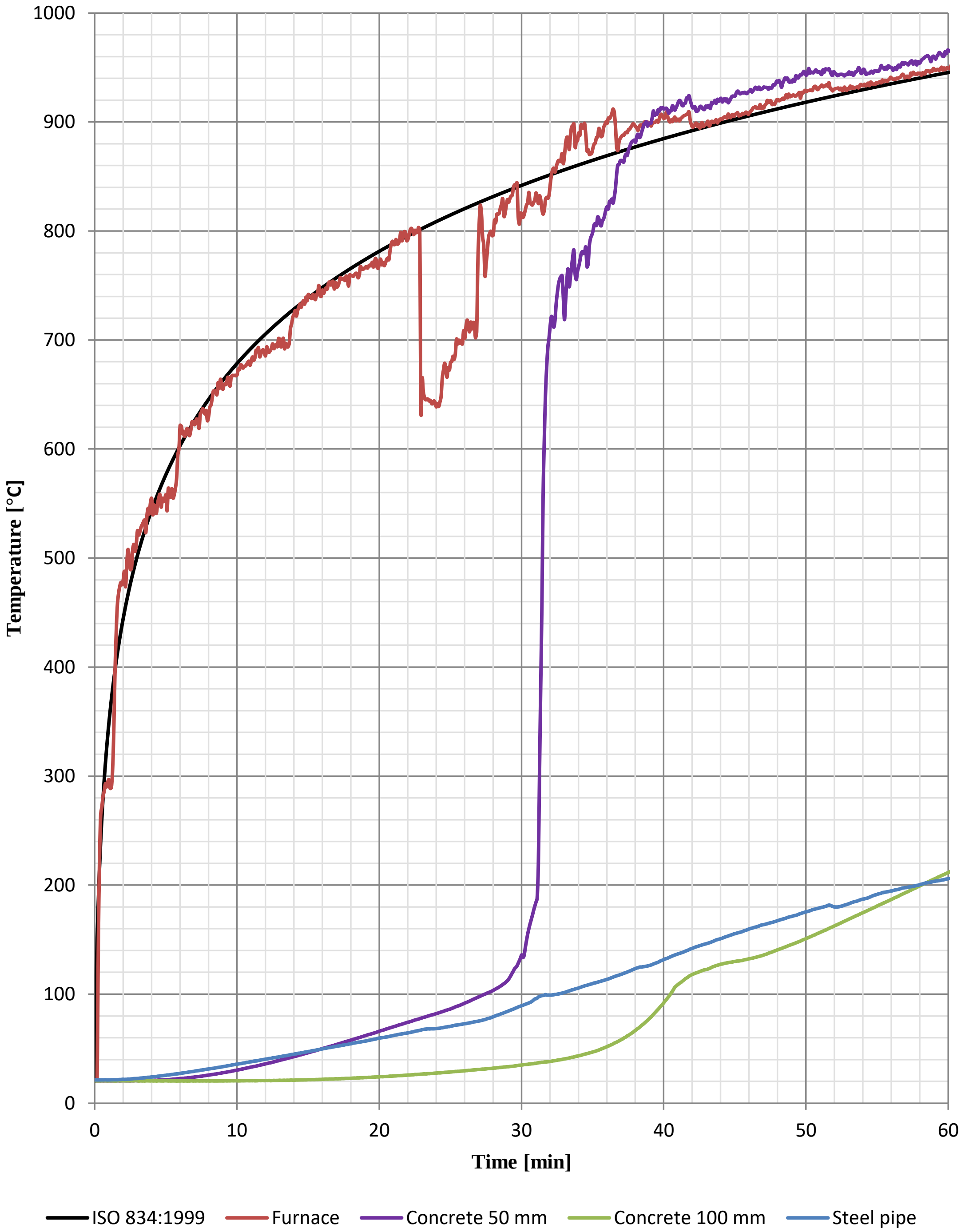

Figure A123. Temperature measurements during the test. The furnace temperature was temporary cooled between 22,3 and 26,8 minutes of the test because high release of vapour during heavy spalling of the test specimen.

Large ring specimen 7: Ø600-300-Mix 6-0.40-1.0kgPP

The test was performed August 29, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts
50:00	Some water is observed on the top of the test specimen.
60:00	Water is observed on the top of the test specimen.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	Amount of spalled concrete [%]	Maximum spalling depth [mm]
-	-	-


Figure A124. Test specimen during the test.

Figure A125. Test specimen after the test.

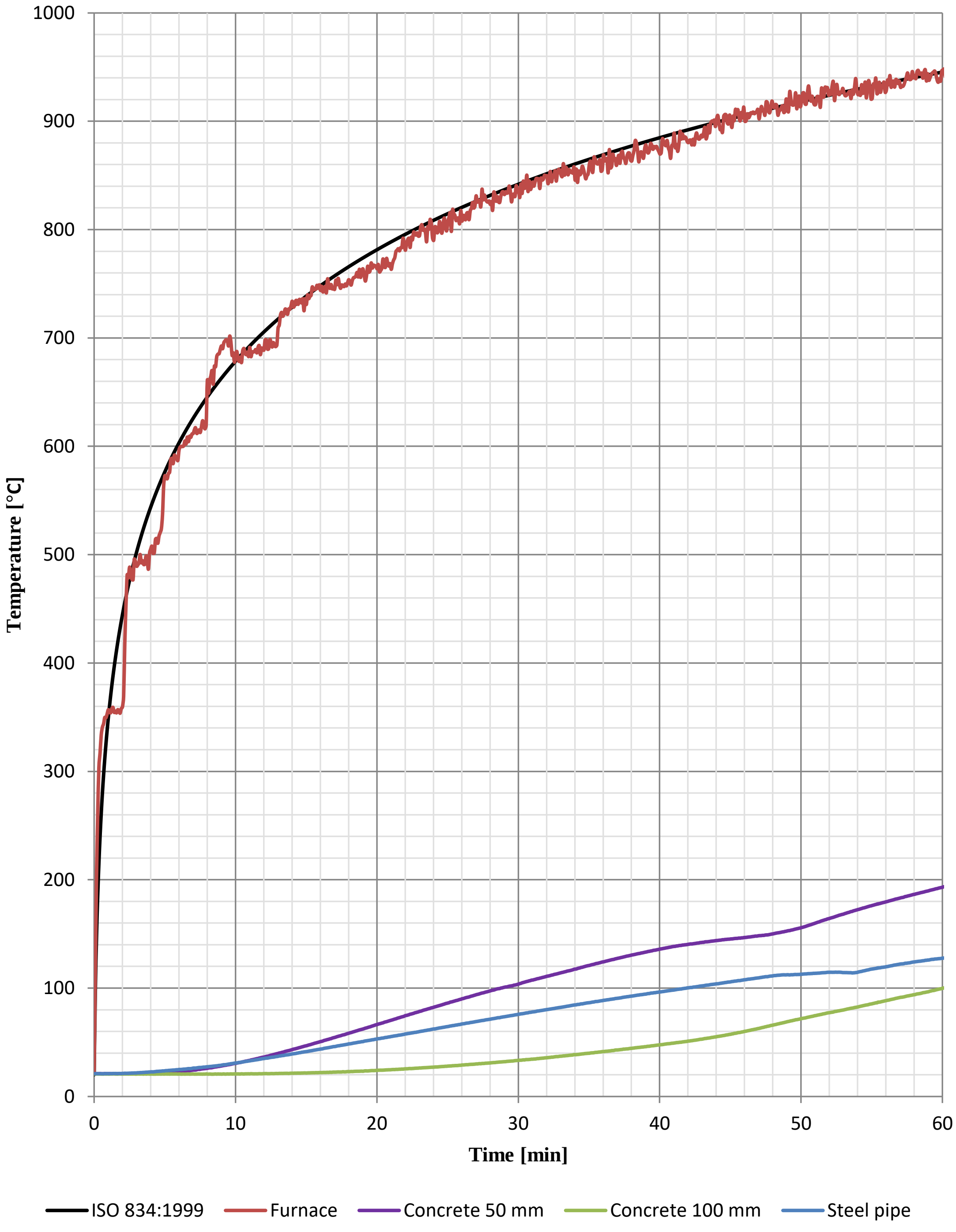

Figure A126. Temperature measurements during the test.

Large ring specimen 8: Ø600-300-Mix 6-0.40-1.0kgPP

The test was performed August 29, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts
48:00	Some water is observed on the top of the test specimen.
60:00	Water is observed on the top of the test specimen.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	Amount of spalled concrete [%]	Maximum spalling depth [mm]
-	-	-

Figure A127. Test specimen during the test.

Figure A128. Test specimen after the test.

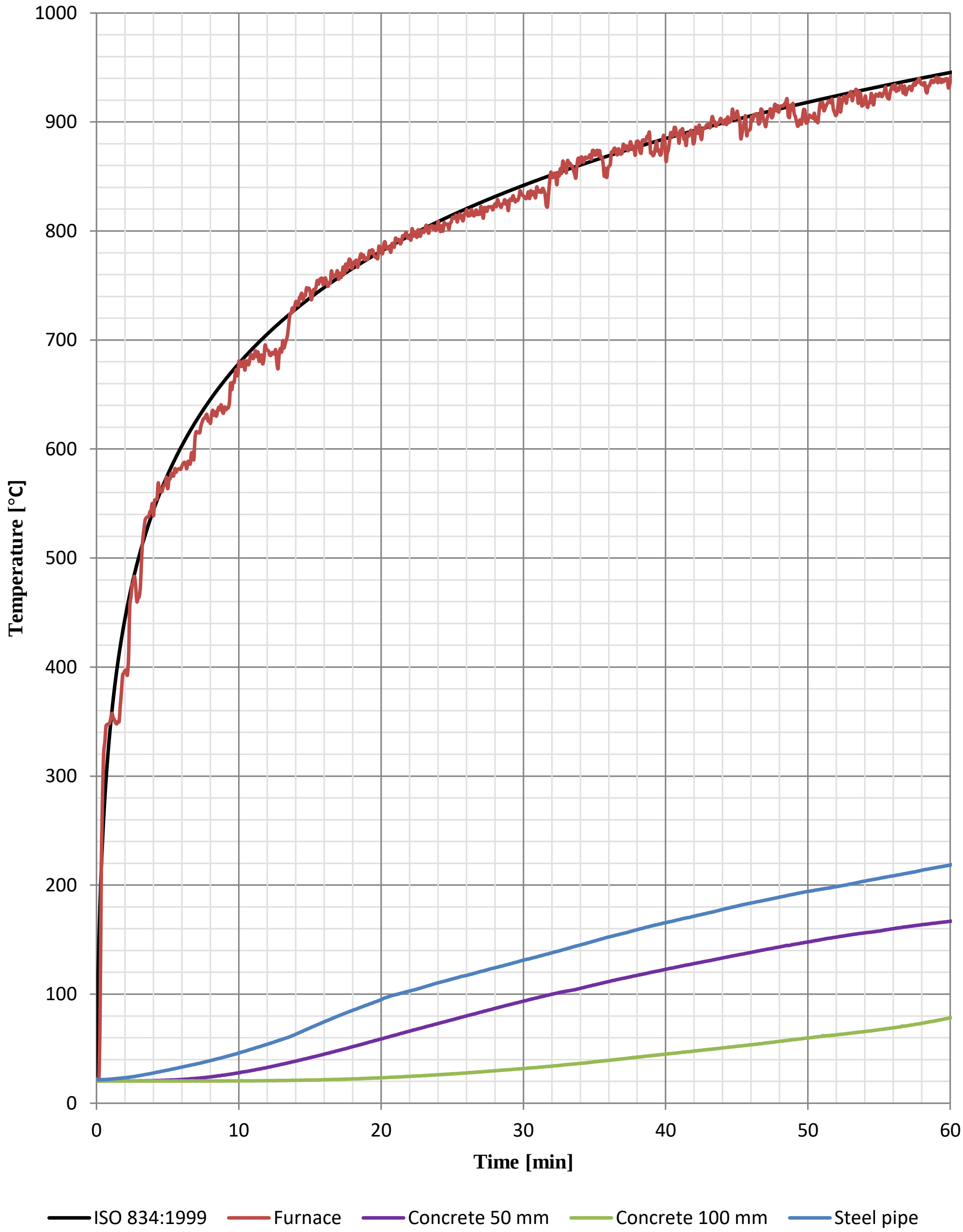

Figure A129. Temperature measurements during the test.

Large ring specimen 9: Ø600-300-Mix 6-0.40-1.0kgPP

The test was performed August 30, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts
40:00	Some water is observed on the top of the test specimen.
60:00	Water is observed on the top of the test specimen.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	Amount of spalled concrete [%]	Maximum spalling depth [mm]
-	-	-

Figure A130. Test specimen during the test.

Figure A131. Test specimen after the test.

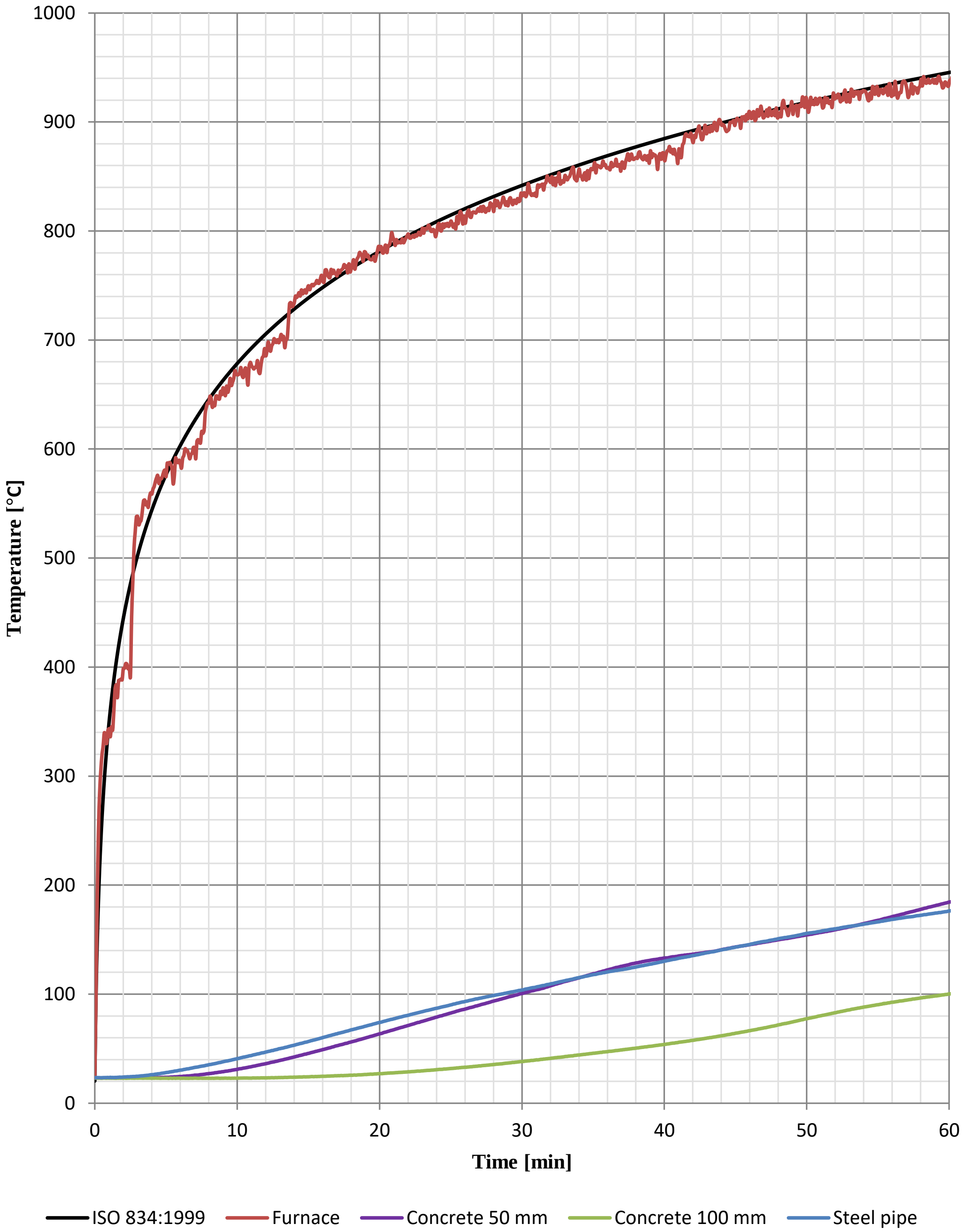

Figure A132. Temperature measurements during the test.

Tests of Small slabs, restrained, test series no 2

Thermocouples

The temperature inside the concrete was measured with totally 2 thermocouples placed in two positions. One was paced 100 mm in to the concrete and the other was placed 50 mm into the concrete on to the reinforcement net from the fire exposed side.

Climate in the furnace

The test of the small scale slabs were performed in accordance with SP Brand 119. The fire exposure was in accordance with ISO 834.

Small Slab, restrained, 10: 500x600-300-Mix 4-0.40-0.0kgPP

The test was performed August 17, 2017.

Time [min:s]	**Observations** **(refer to the non-flame side if nothing else is stated)**
00:00	The test starts
08:30	A bang is heard from the test specimen.
09:45	A bang is heard from the test specimen.
11:20	Two bangs are heard from the test specimen.
11:50	Continuous spalling.
24:00	Some water is observed on the vertical sides of the test specimen.
30:00	The spalling ends.
60:00	Water is observed on the sides of the test specimen.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	**Amount of spalled concrete [%]**	**Maximum spalling depth [mm]**
19.6	6.4	65

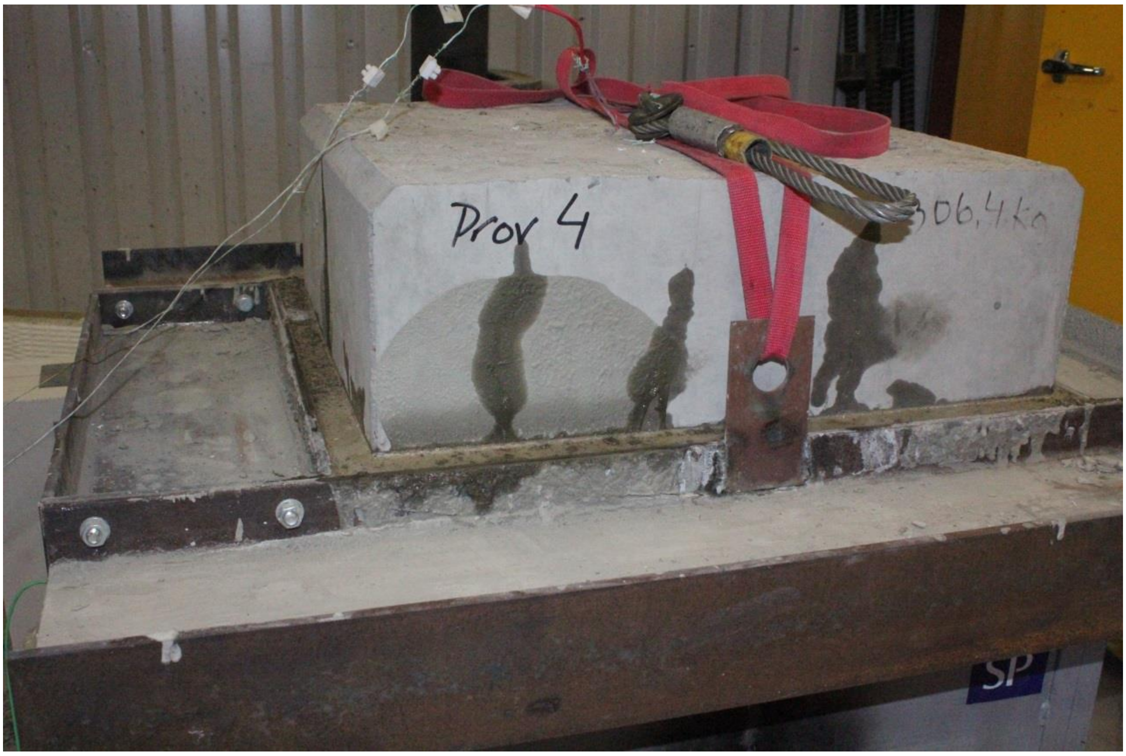

Figure A133. Test specimen during the test.

Figure A134. Test specimen after the test.

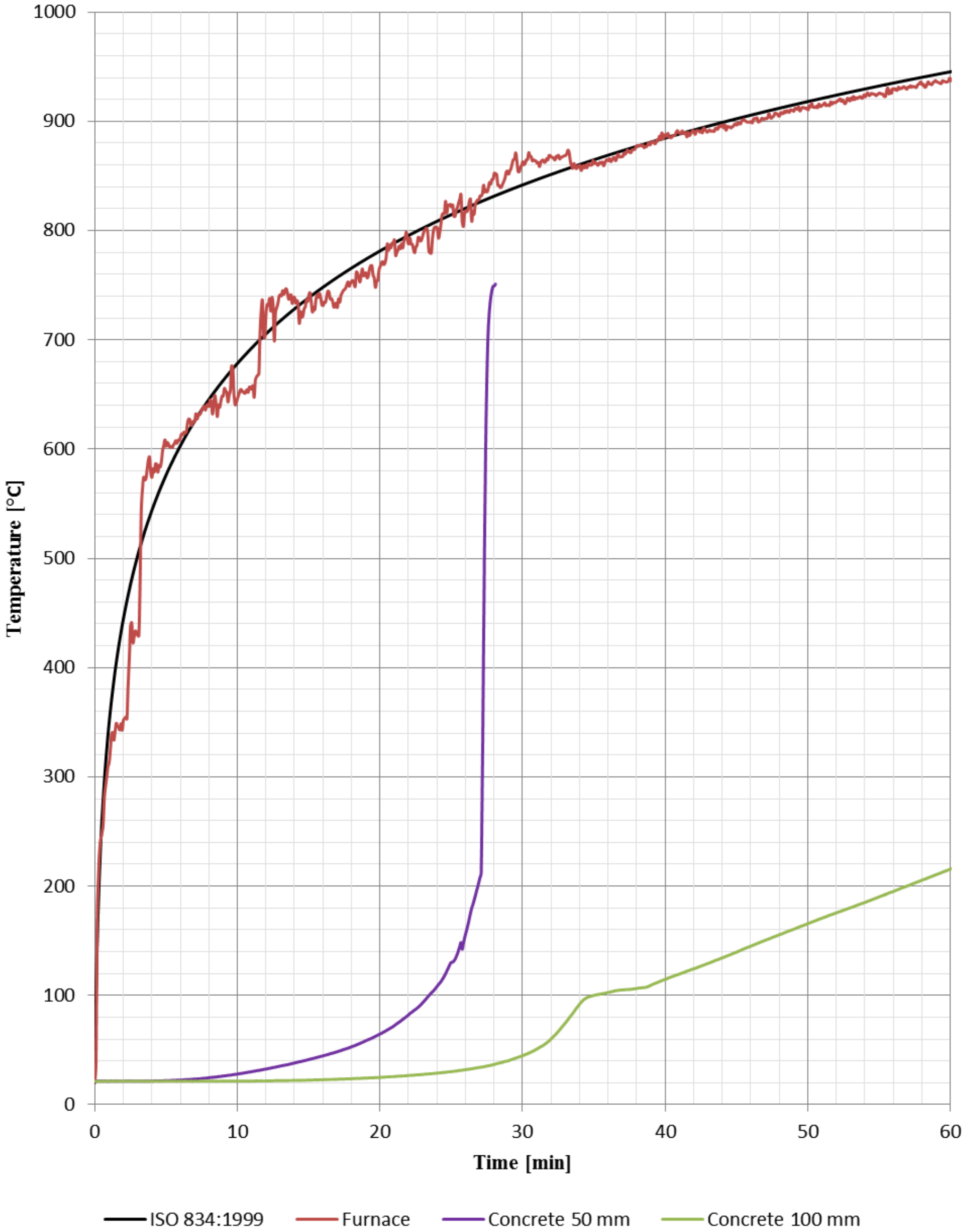

Figure A135. Temperature measurements during the test. Thermocouple Concrete 50 mm was out of order after 28,1 minutes of the test.

Small Slab, restrained, 11: 500x600-300-Mix 4-0.40-0.0kgPP

The test was performed August 17, 2017.

Time [min:s]	**Observations** **(refer to the non-flame side if nothing else is stated)**
00:00	The test starts
11:00	A bang is heard from the test specimen.
11:50	A bang is heard from the test specimen.
12:15	Continuous spalling.
23:00	Some water is observed on the vertical sides of the test specimen.
35:00	The spalling ends.
60:00	Water is observed on the vertical sides of the test specimen.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	**Amount of spalled concrete [%]**	**Maximum spalling depth [mm]**
24.4	8.0	82

Figure A136. Test specimen during the test.

Figure A137. Test specimen after the test.

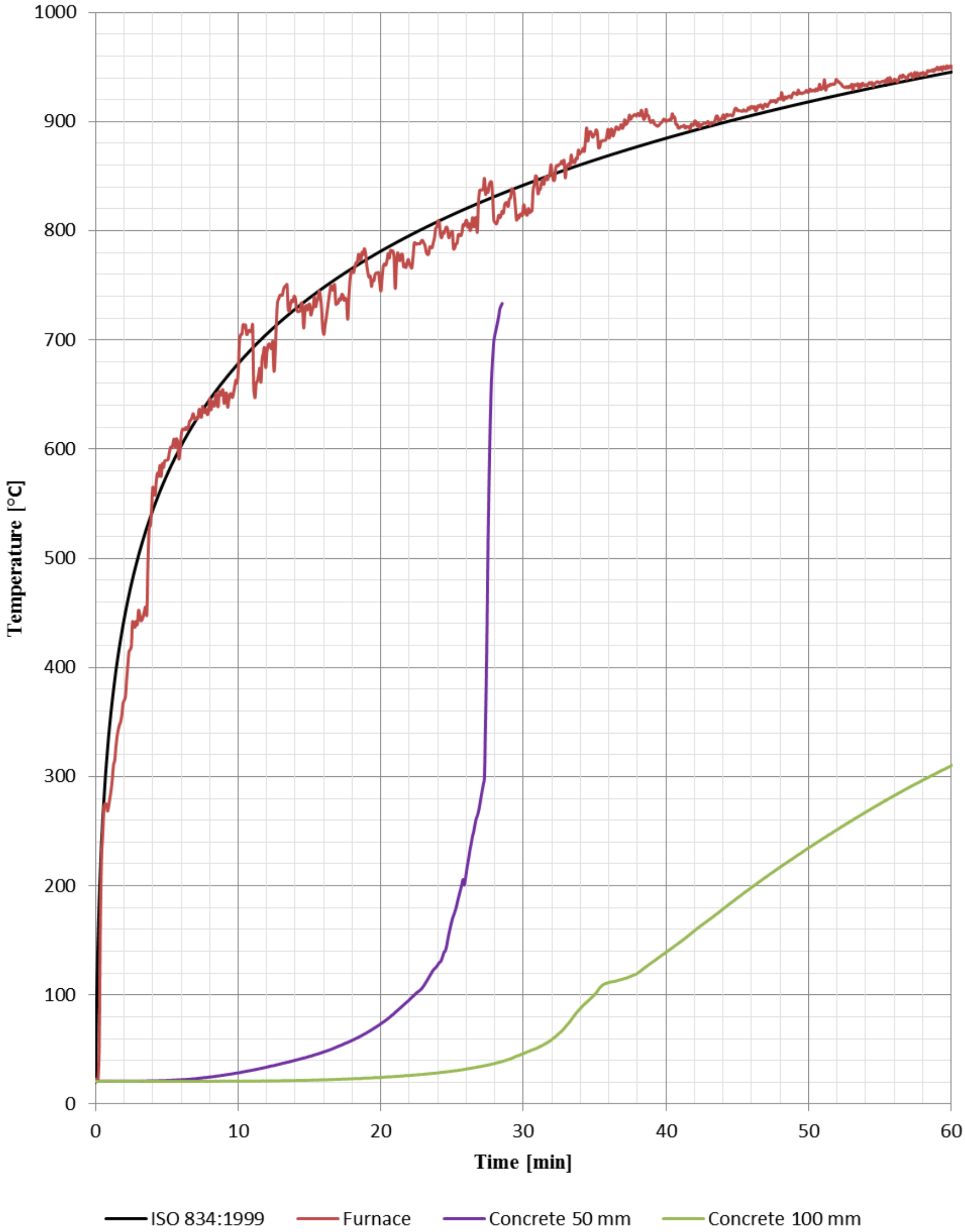

Figure A138. Temperature measurements during the test. Thermocouple Concrete 50 mm was out of order after 28,6 minutes of the test.

Small Slab, restrained, 13: 500x600-300-Mix 5-0.40-0.2kgPP

The test was performed August 23, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts
20:00	Some water is observed on the vertical sides of the test specimen.
60:00	Water is observed on the vertical sides of the test specimen.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	Amount of spalled concrete [%]	Maximum spalling depth [mm]
-	-	-

Figure A139. Test specimen during the test.

Figure A140. Test specimen after the test.

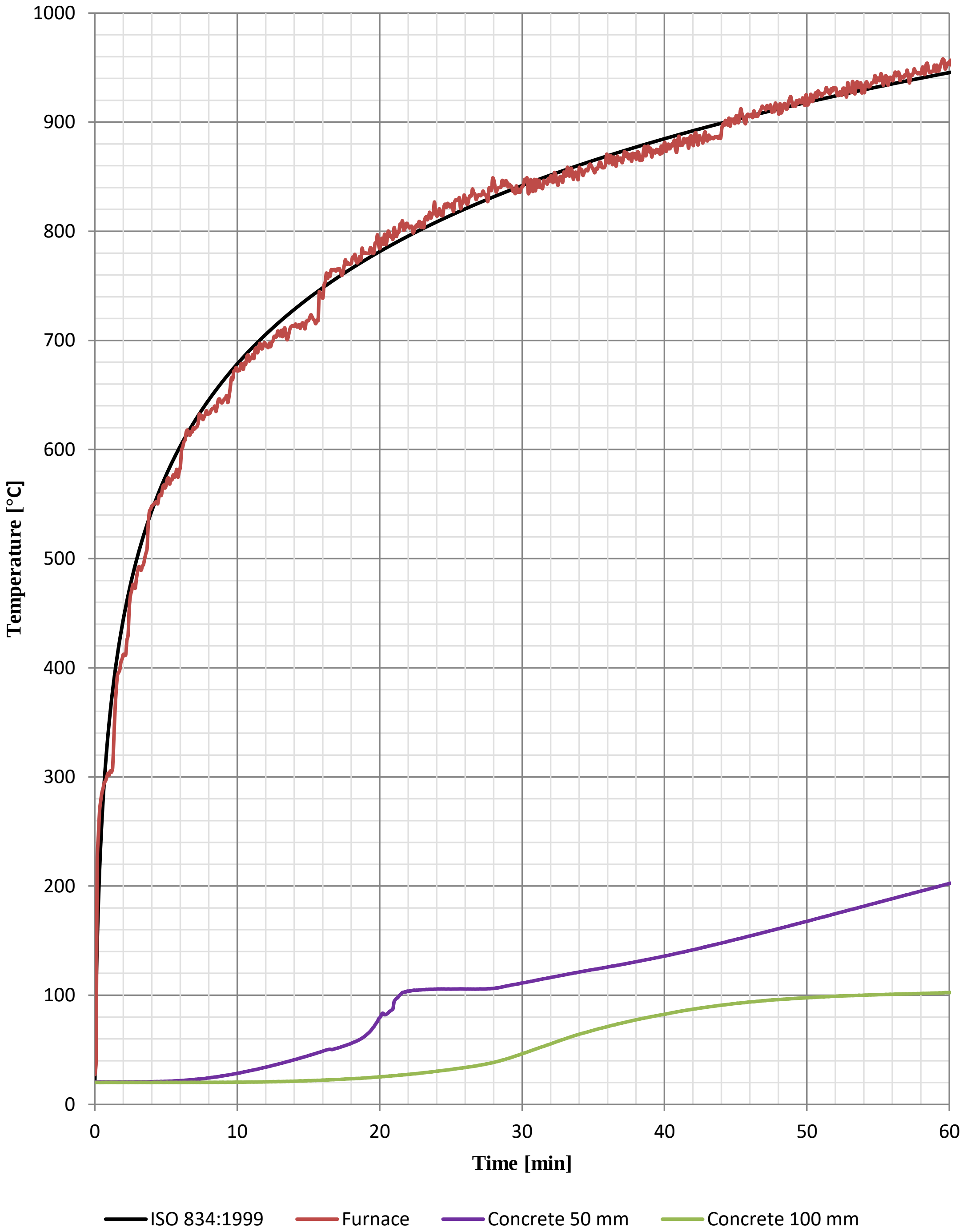

Figure A141. Temperature measurements during the test.

Small Slab, restrained, 14: 500x600-300-Mix 5-0.40-0.2kgPP

The test was performed August 23, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts
16:00	A bang is heard from the test specimen.
17:55	A small bang is heard from the test specimen.
18:55	Two small bangs are heard from the test specimen.
20:00	Continuous spalling.
25:00	The spalling ends.
30:00	Some water is observed on the vertical sides of the test specimen.
60:00	Water is observed on the vertical sides of the test specimen.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	Amount of spalled concrete [%]	Maximum spalling depth [mm]
15.0	4.9	45

Figure A142. Test specimen during the test.

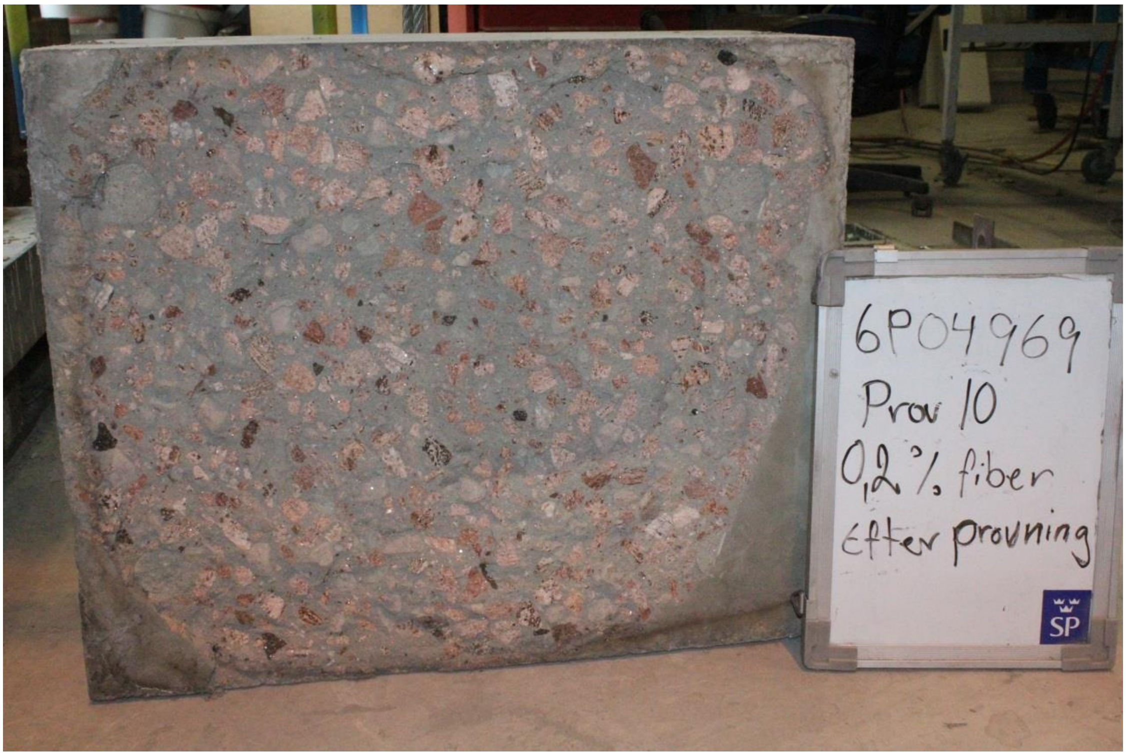

Figure A143. Test specimen after the test.

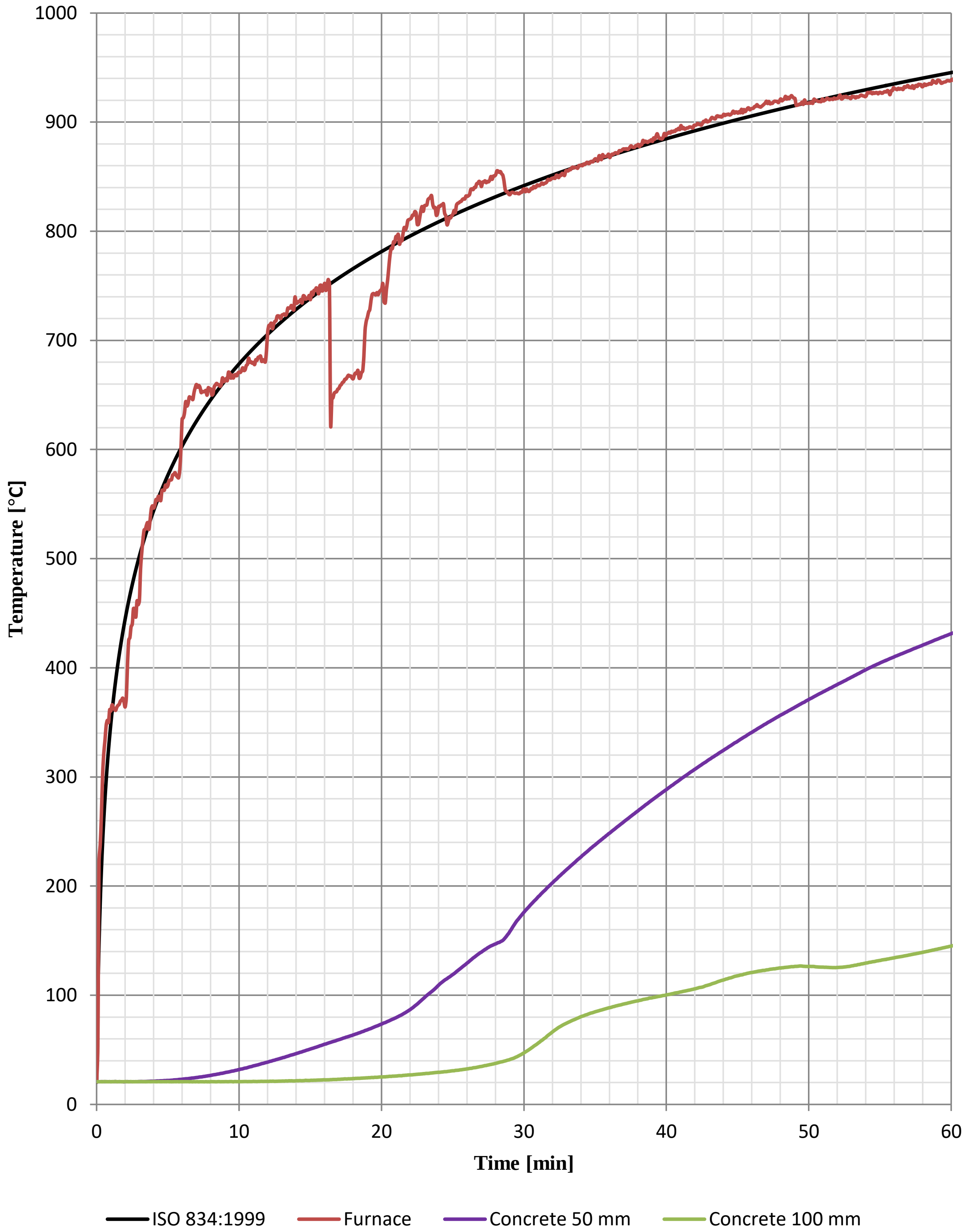

Figure A144. Temperature measurements during the test. The furnace temperature was temporary cooled between 16,1 and 20,0 minutes of the test because high release of vapour during heavy spalling of the test specimen.

Small Slab, restrained, 16: 500x600-300-Mix 6-0.40-1.0kgPP

The test was performed September 5, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts
30:00	Water is observed on three vertical sides of the test specimen.
60:00	Water is observed on three vertical sides of the test specimen.
61:00	The test terminates.

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	Amount of spalled concrete [%]	Maximum spalling depth [mm]
-	-	-

Figure A145. Test specimen during the test.

Figure A146. Test specimen after the test.

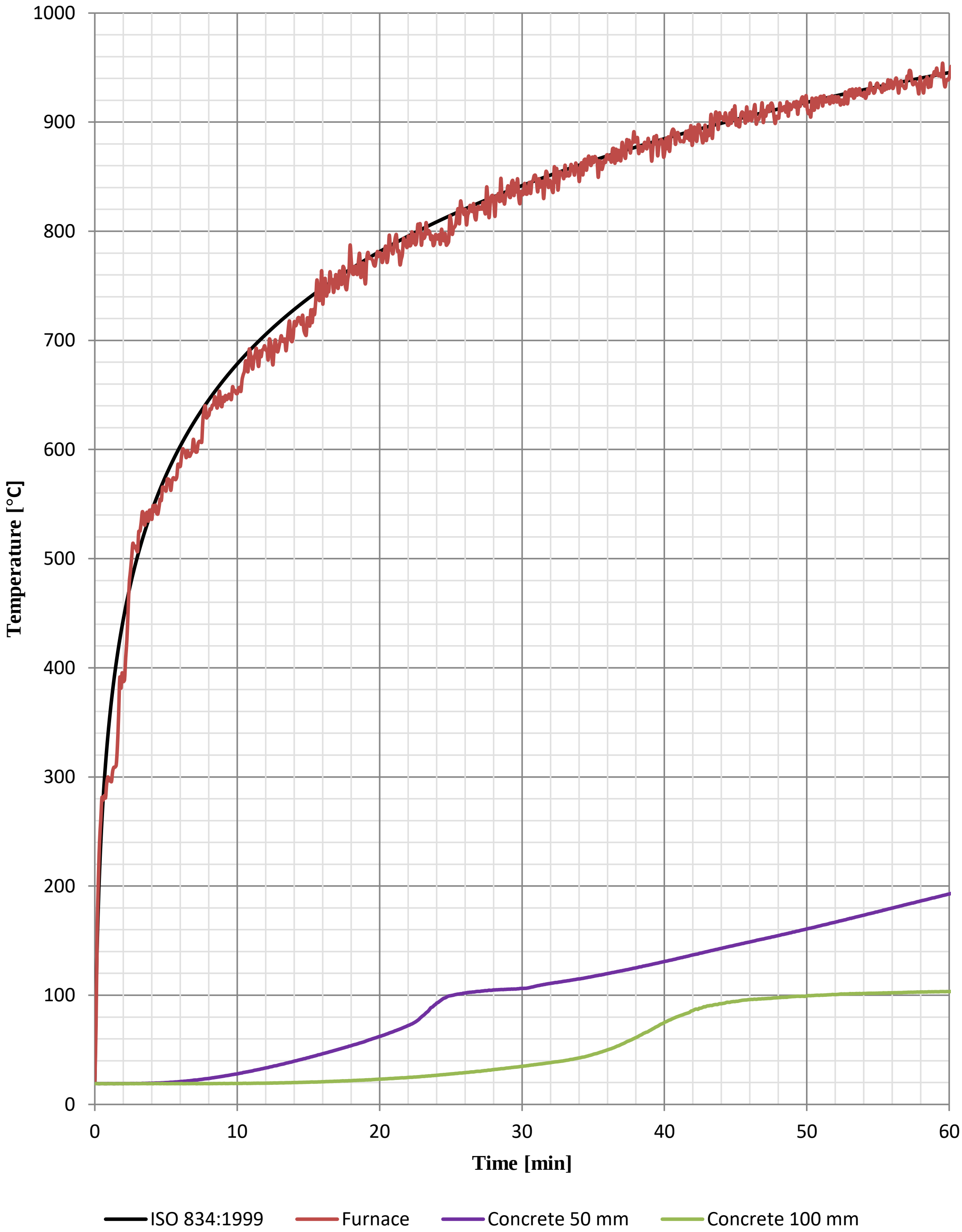

Figure A147. Temperature measurements during the test.

Small Slab, restrained, 17: 500x600-300-Mix 6-0.40-1.0kgPP

The test was performed September 4, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	The test starts
30:00	Some water is observed on the vertical sides of the test specimen.
60:00	Water is observed on the vertical sides of the test specimen.
61:00	The test terminates

The spalling of the slab was evaluated and measured after the test. The weight of the slab was measured before and after the test and the position of maximum spalling depth was evaluated and measured.

Weight of spalled concrete [kg]	Amount of spalled concrete [%]	Maximum spalling depth [mm]
-	-	-

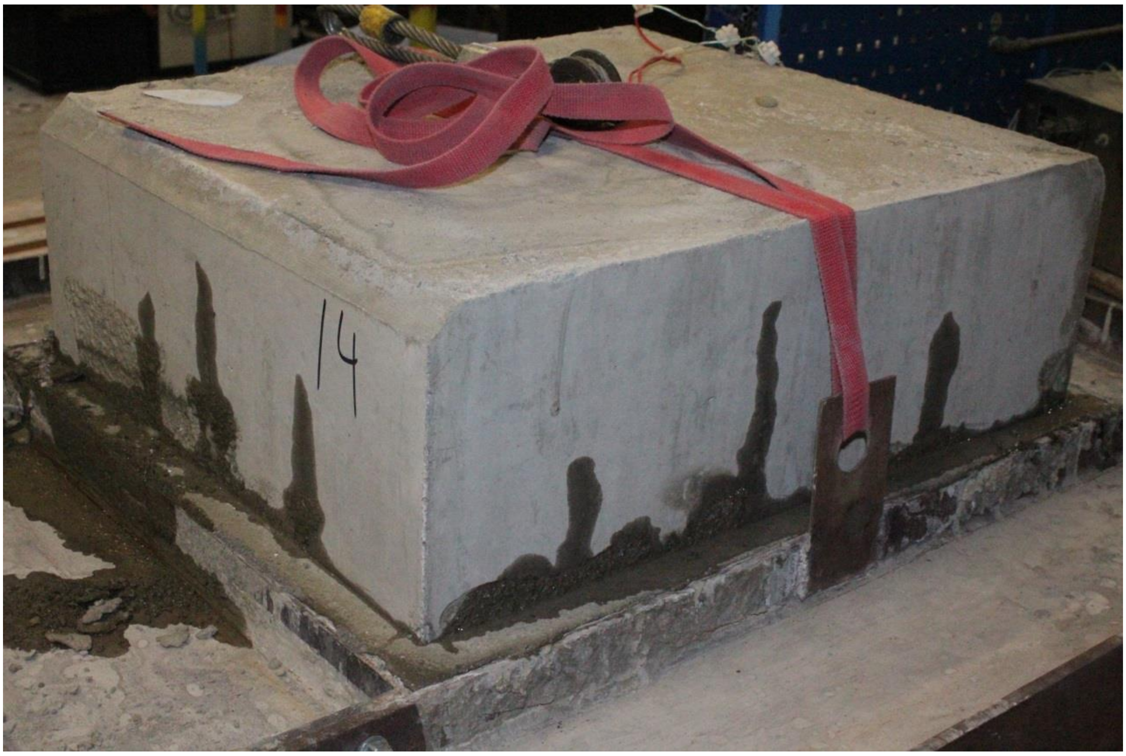

Figure A148. Test specimens during the test.

Figure A149. Test specimen after the test.

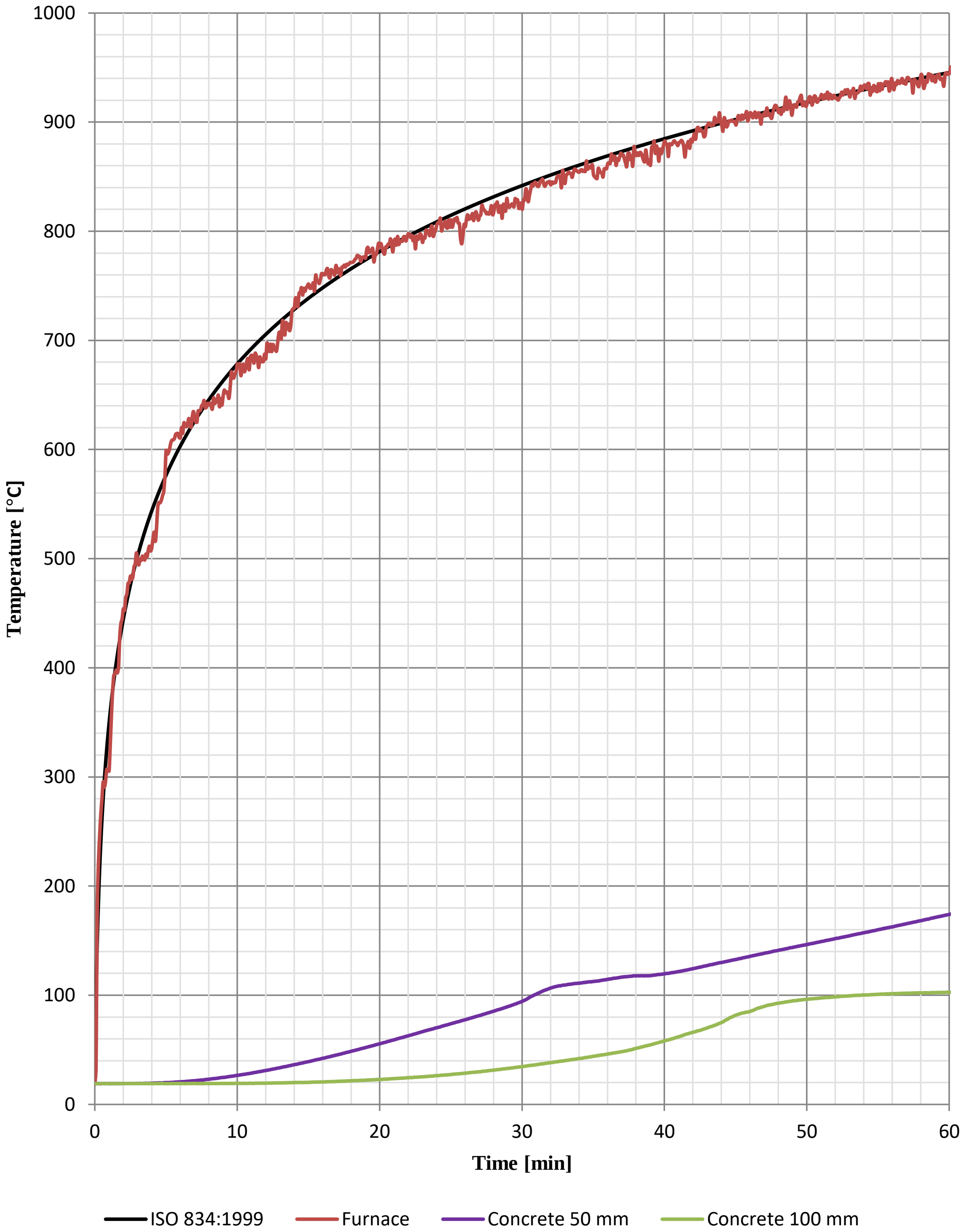

Figure A150. Temperature measurements during the test.

Large scale, vertical, loaded tests, test series 2

Large slab, vertical, loaded, 19: 3100x1200-300-Mix 4-0.40-0.0kgPP

The test was performed August 11, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	Test starts
07:20	First spalling. At the edges of the slabs.
08:50	Spalling from the whole fire exposed surface.
10:00	Approx. 50 % of the surface has spalled.
12:10	The whole surface is spalled.
21:20	The spalling is approx. 50 mm. It is possible to see the reinforcements 50 mm in to the slab.
27:50	The concrete slab collapses at the lower edge. A triangular part of concrete has sheared of along the full width. The break is approx. 120 mm from the fire exposed side.
30:10	The spalling has stopped at the depth of the reinforcement.
32:20	The slab is cracked on the sides.
42:30	Water is coming out from the cracks described at 32:20.
51:10	The concrete slab collapses at the upper edge. A triangular part of concrete has sheared of along the full width. The break is approx. 200 mm from the fire exposed side.
51:40	The test is stopped.

The spalling of the slab was measured after the test. The measurements were made at the junction between 1/3 width and at 1/5 height of the slab. The position of maximum spalling depth were also evaluated and measured.
The result from the measurement of spalling is described in the figure below.

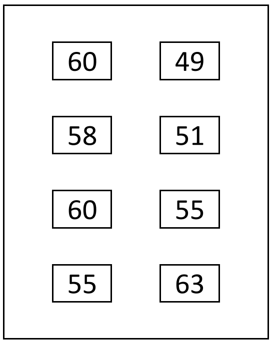

Figure A151. Measured spalling depth after the test (mm).

Maximum spalling: 72 mm.

Figure A152. Test specimen after the test. The whole surface is spalled to the depth of the reinforcement.

Figure A153. The test setup at the beginning of the test.

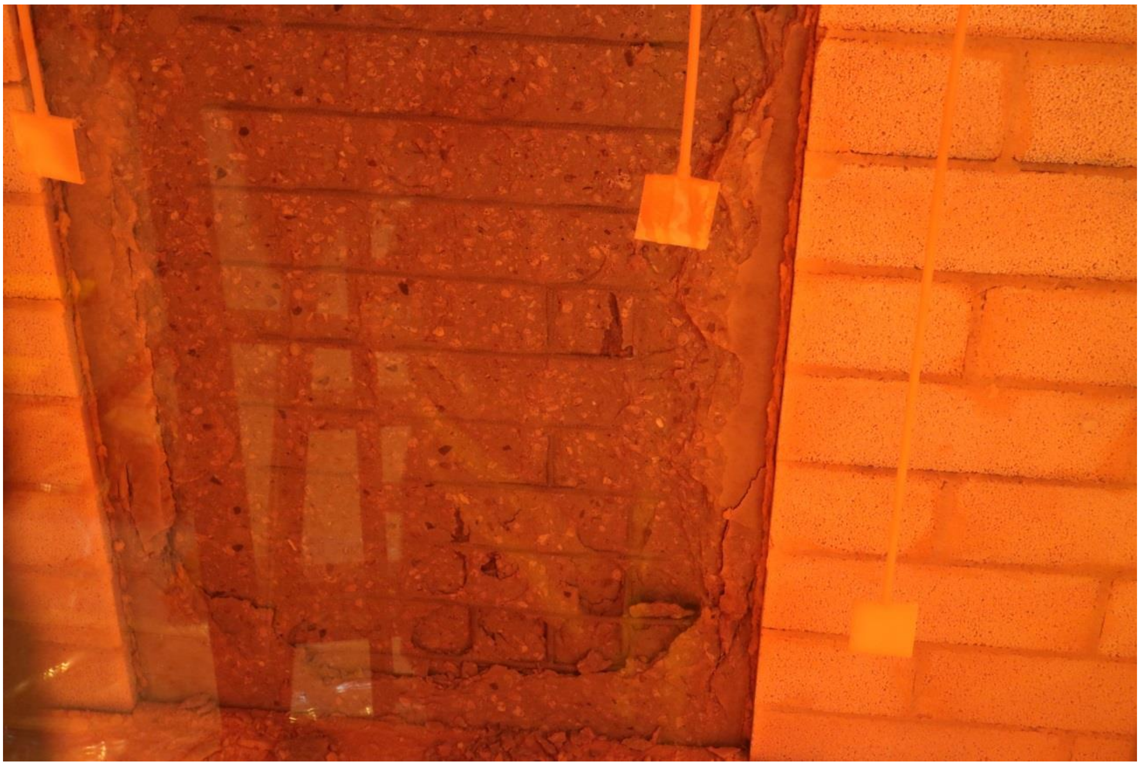
Figure A154. The fire exposed side after 39 minutes of the test.


Figure A155. The slab is cracked at the bottom.

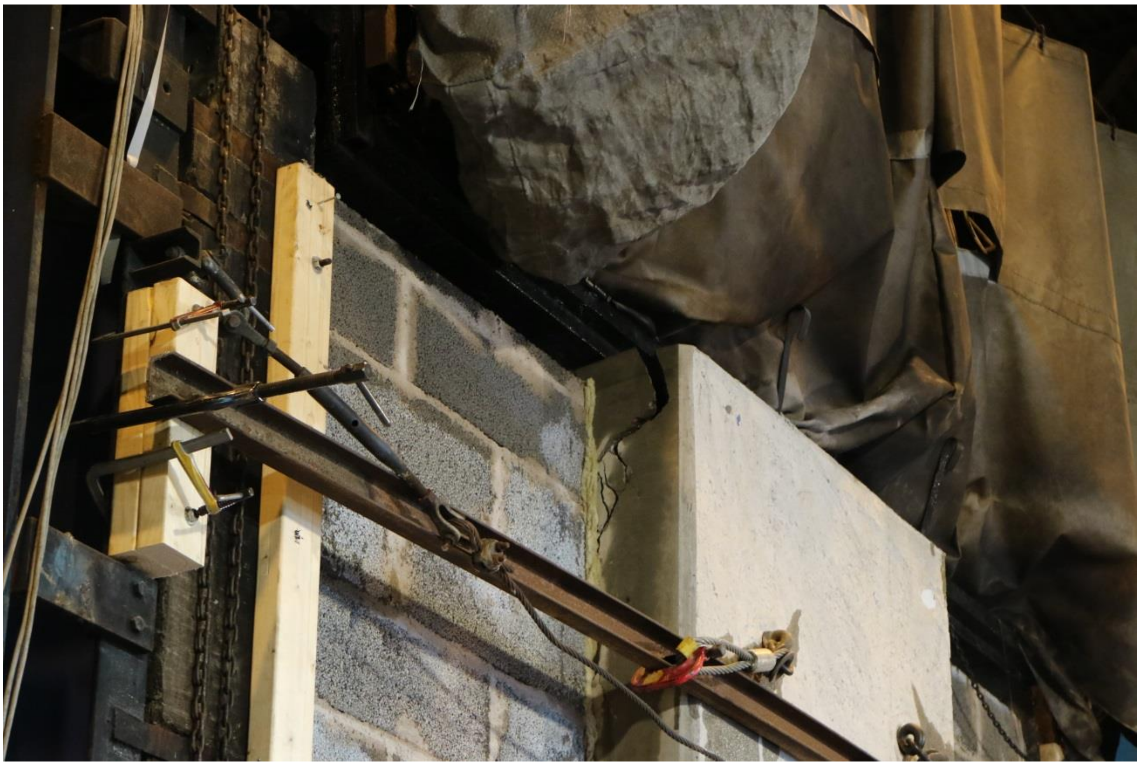
Figure A156. The slab is cracked at the top.

The temperature inside the concrete was measured with totally 10 thermocouples placed in two planes parallel to the fire exposed surface. One plane was paced 100 mm in to the concrete and the other was placed 50 mm into the concrete on to the reinforcement net.

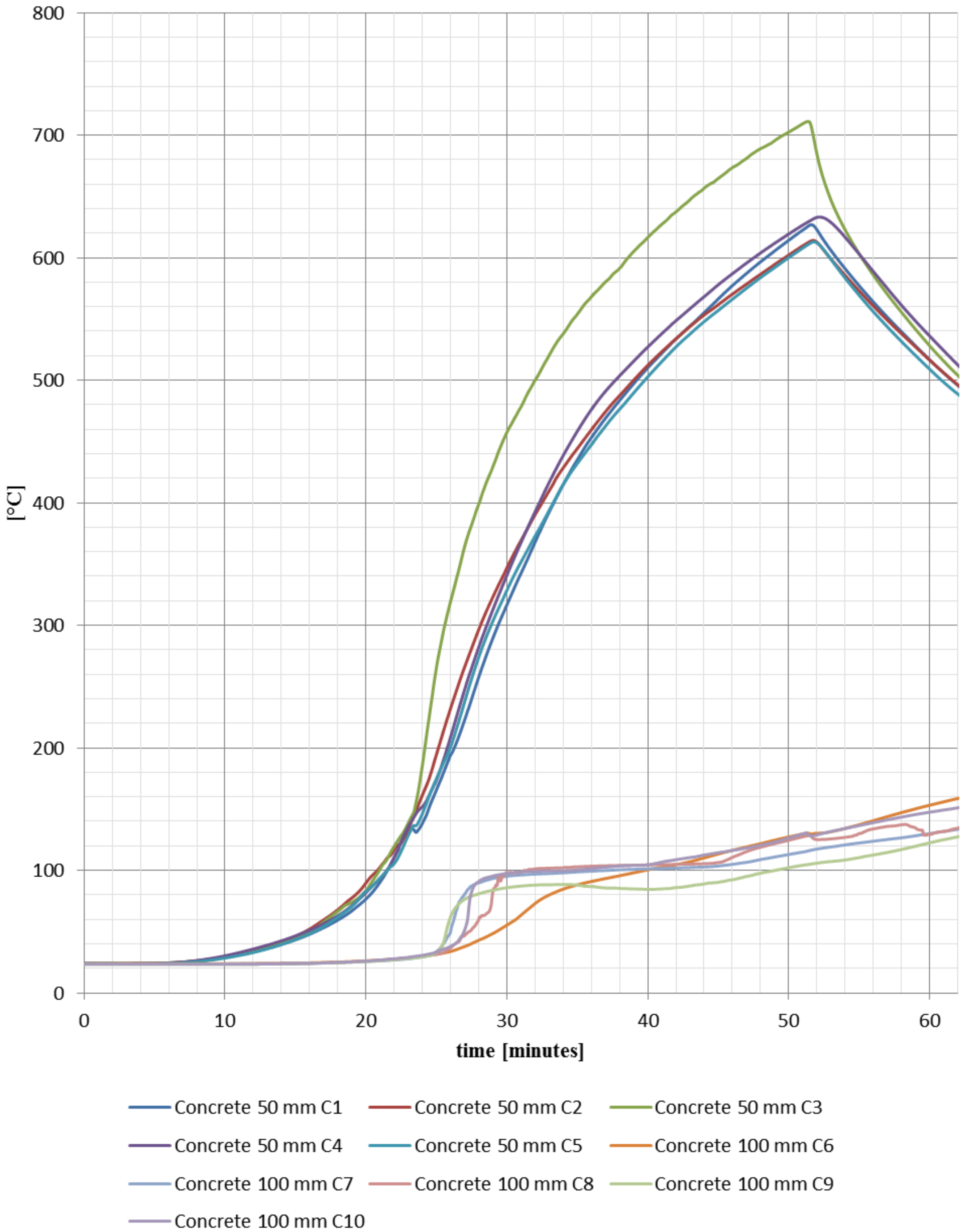

Figure A157. Temperature measurements in the concrete during the test.

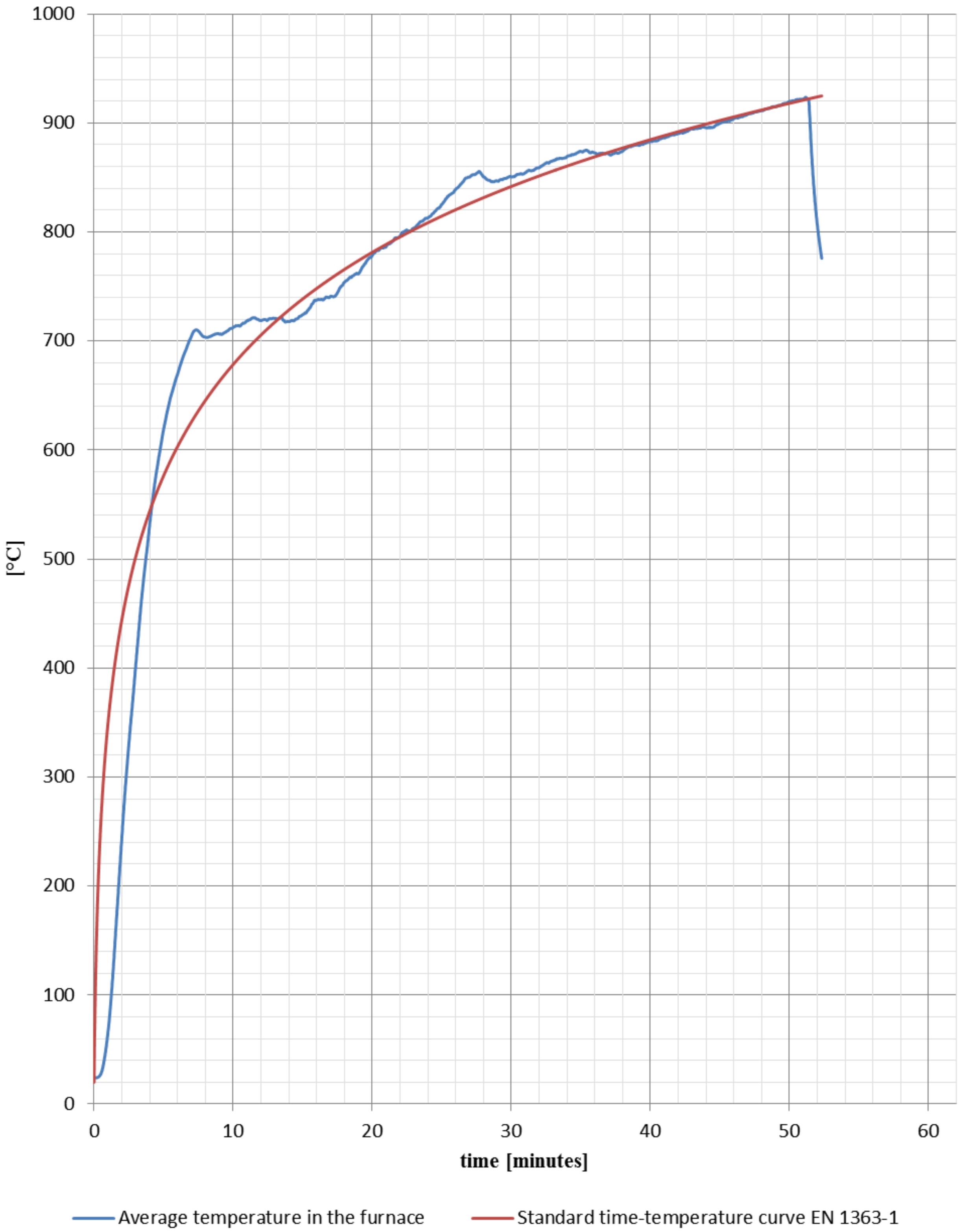

Figure A158. Average temperature in the furnace during the test.

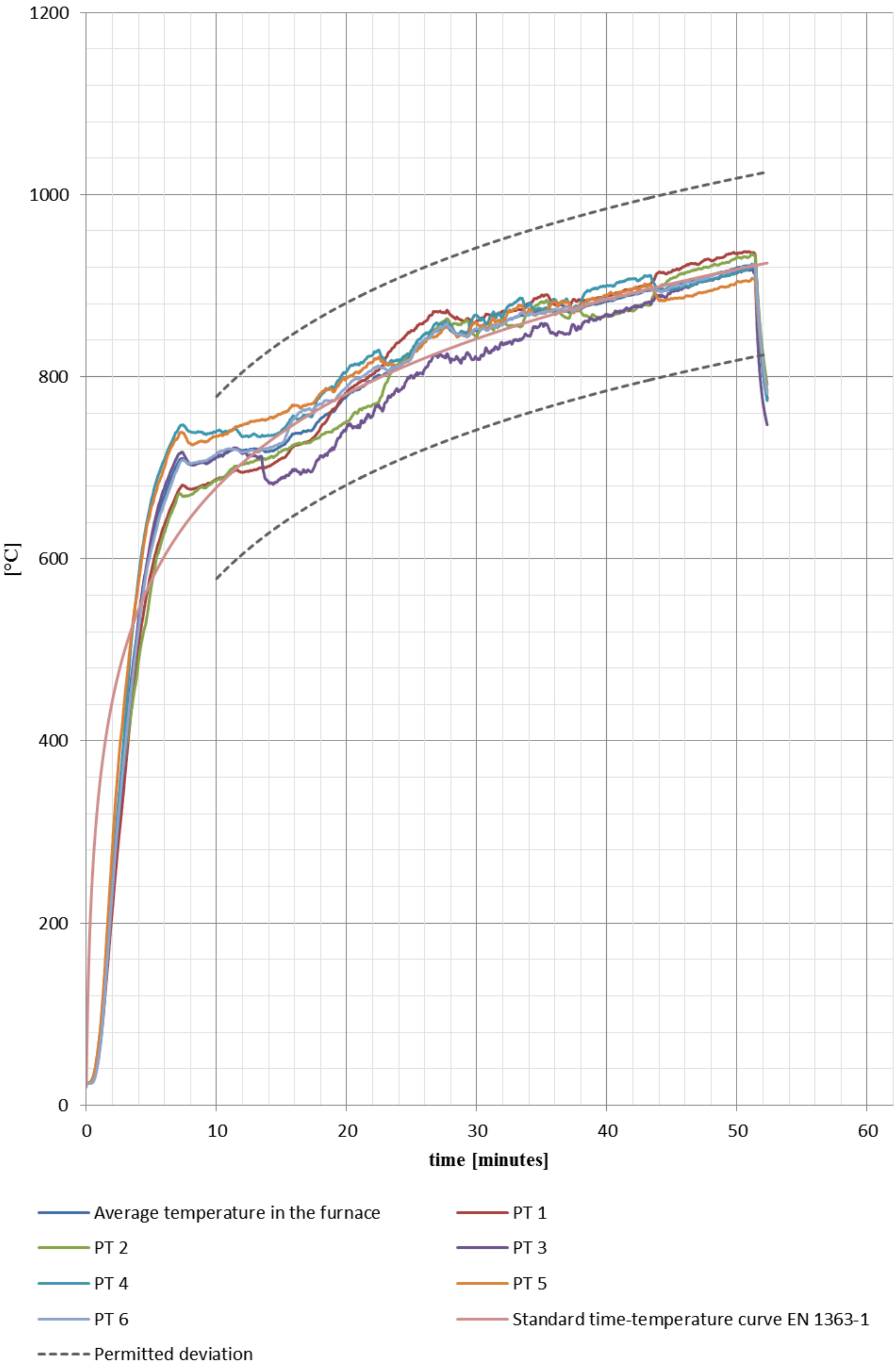

Figure A159. Measured temperature in the furnace during the test.

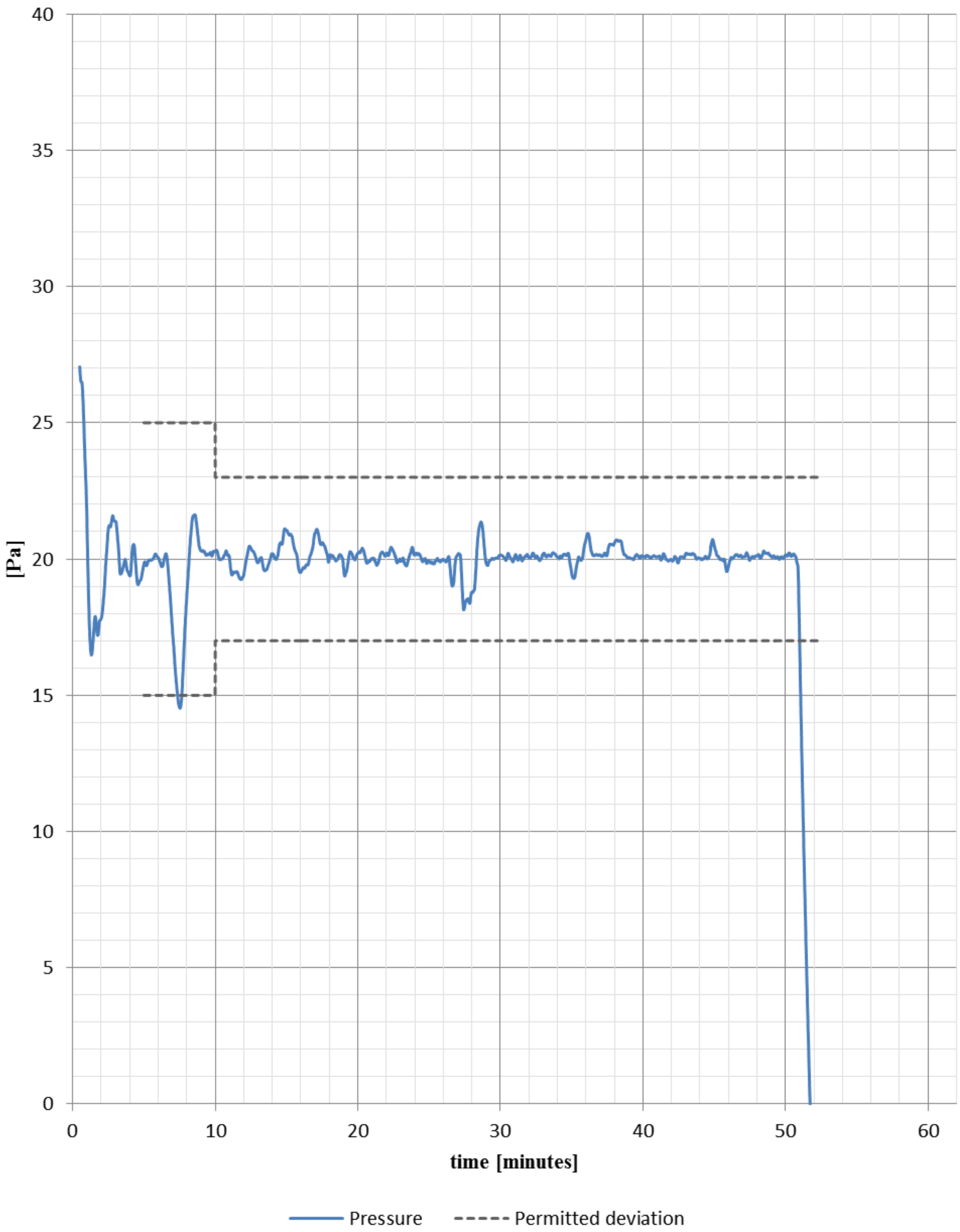

Figure A160. Measured pressure difference between the pressure in the furnace and the ambient pressure during the test.

Large slab, vertical, loaded, 20: 3100x1200-300-Mix 5-0.40-0.2kgPP

The test was performed October 13, 2017.

Time [min:s]	**Observations** **(refer to the non-flame side if nothing else is stated)**
00:00	Test starts
04:30	First spalling. A surface of approx. 1,5 x 0,5 m in the centre of the slab spalls off. Some spalling from time to time.
16:00	Spalling from the whole fire exposed surface. Approx. 2-3 cm has spalled off.
22:00	Continuous spalling. The depth of the spalling is not to the reinforcement.
23:50	Water is coming out from the non-fire exposed side of the slab.
25:50	It is possible to see the reinforcements 50 mm in to the slab at some parts.
38:30	Some spalling from the concrete behind the reinforcement.
31:30	The spalling has stopped approx. at the depth of the reinforcement.
34:20	The slab is cracked on the sides. Water is coming out from the cracks.
61:20	The test is stopped.

The spalling of the slab was measured after the test. The measurements were made at the junction between 1/3 width and at 1/5 height of the slab. The position of maximum spalling depth was also evaluated and measured.

The result from the measurement of spalling is described in the figure below.

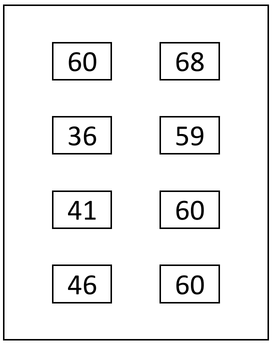

Figure A161. Measured spalling depth after the test (mm).

Maximum spalling: 76 mm

The surface of the test sample after the test is show in the photograph below.

Figure A162. Test specimen after the test. The whole surface is spalled to the depth of the reinforcement

The temperature inside the concrete was measured with totally 10 thermocouples placed in two planes parallel to the fire exposed surface. One plane was paced 100 mm in to the concrete and the other was placed 50 mm into the concrete on to the reinforcement net.

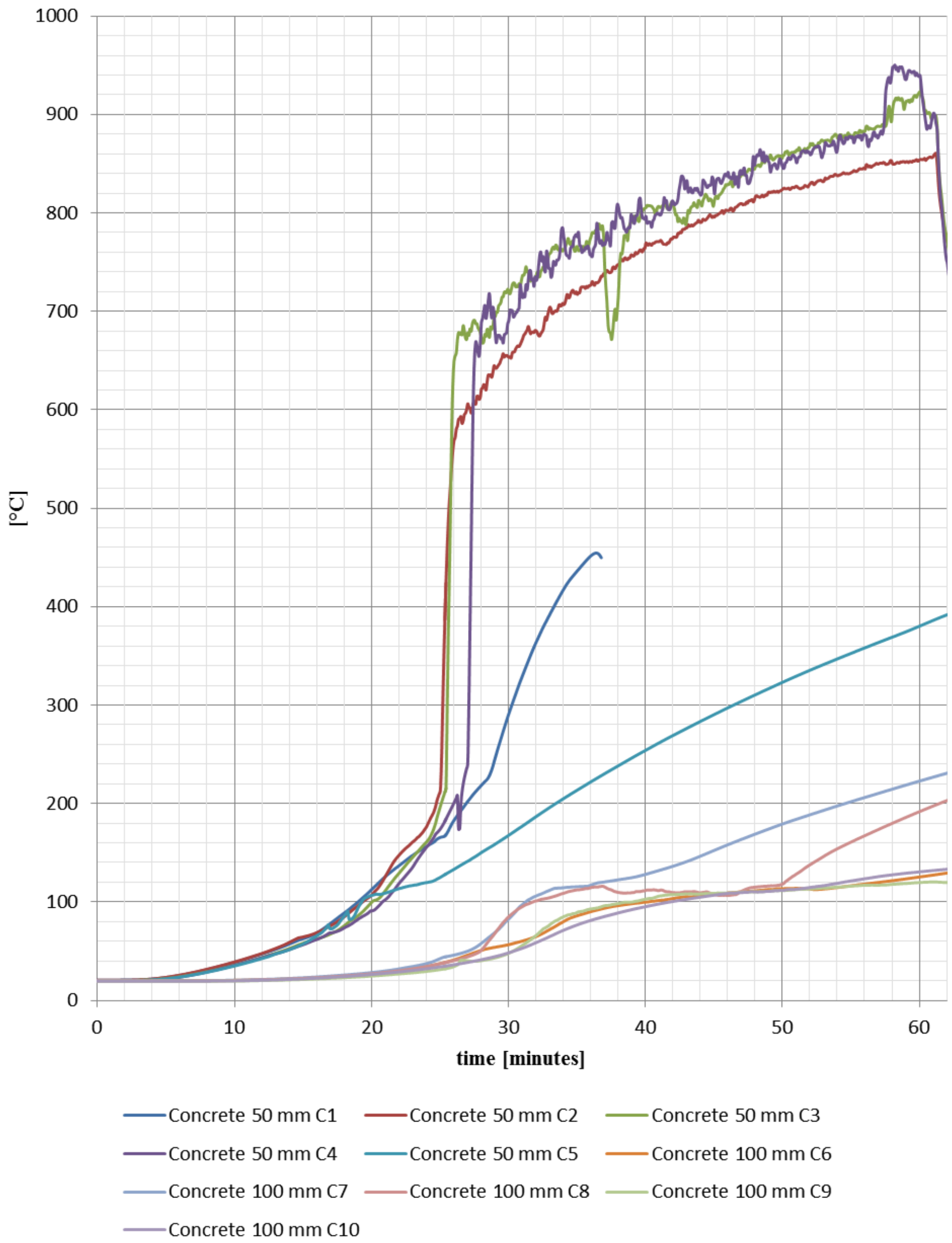

Figure A163. Measured temperatures in the concrete during the test. Thermocouple Concrete 50 mm C1 was out of order from 36,8 minutes of the test.

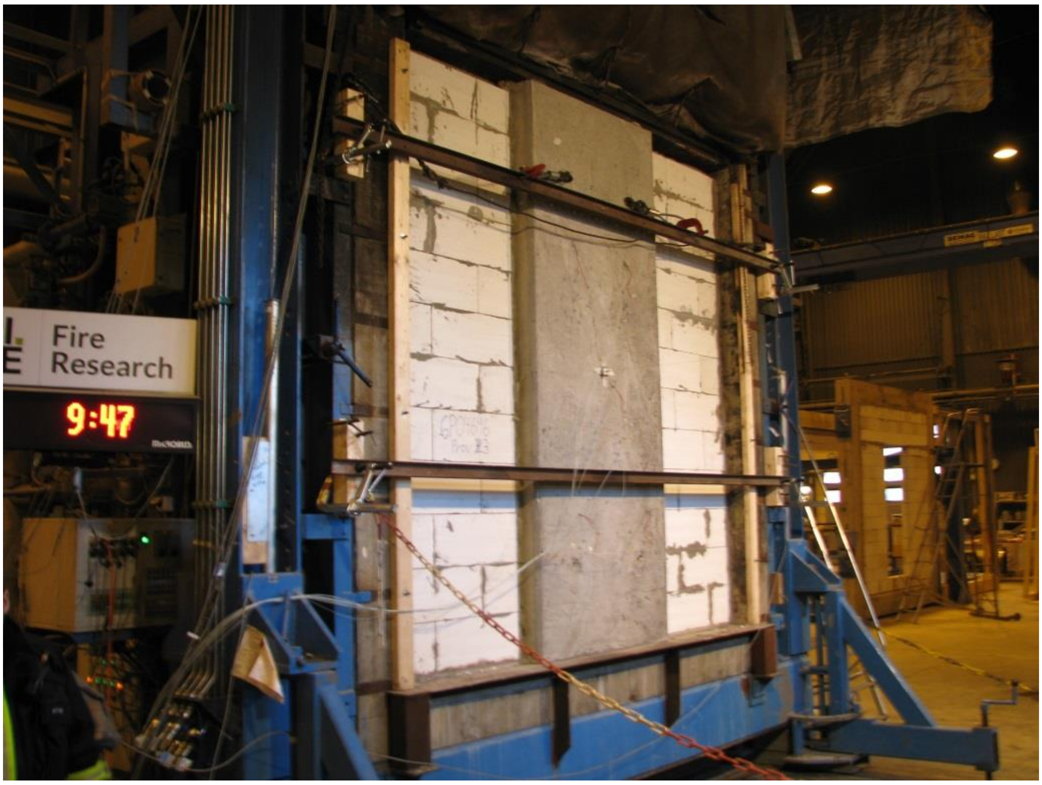

Figure A164. The test setup at the beginning of the test.

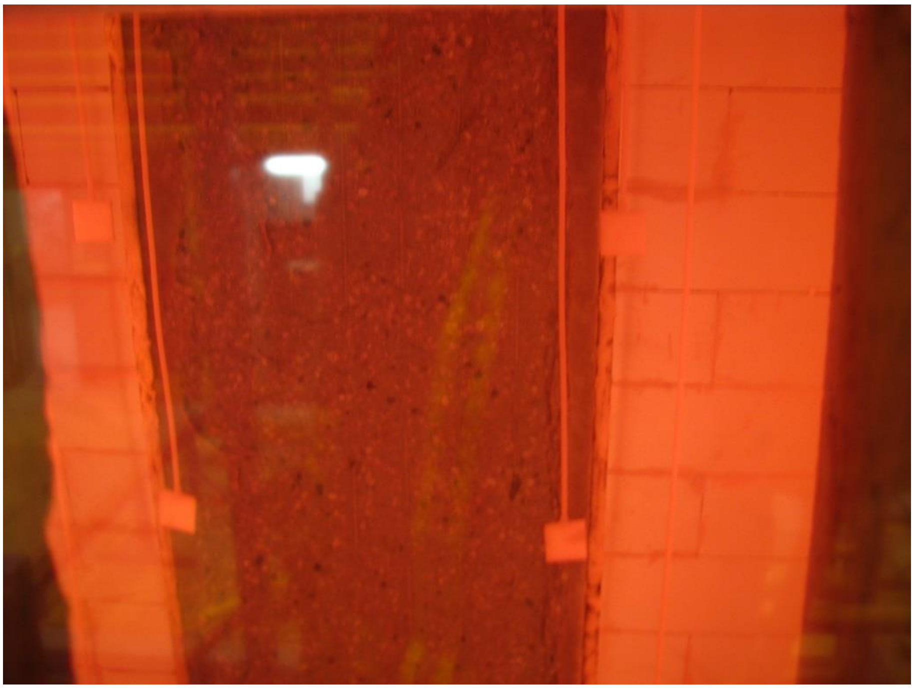
Figure A165. The fire exposed side after 25 minutes of the test.

Figure A166. The slab after the test. The slab is cracked on the sides. Water is coming out from the cracks.

The temperature in the furnace was controlled in accordance with EN 1363-1:2012. The pressure in the furnace was controlled to +20Pa at the top of the test specimen.

The climate in the furnace during the test is described below.

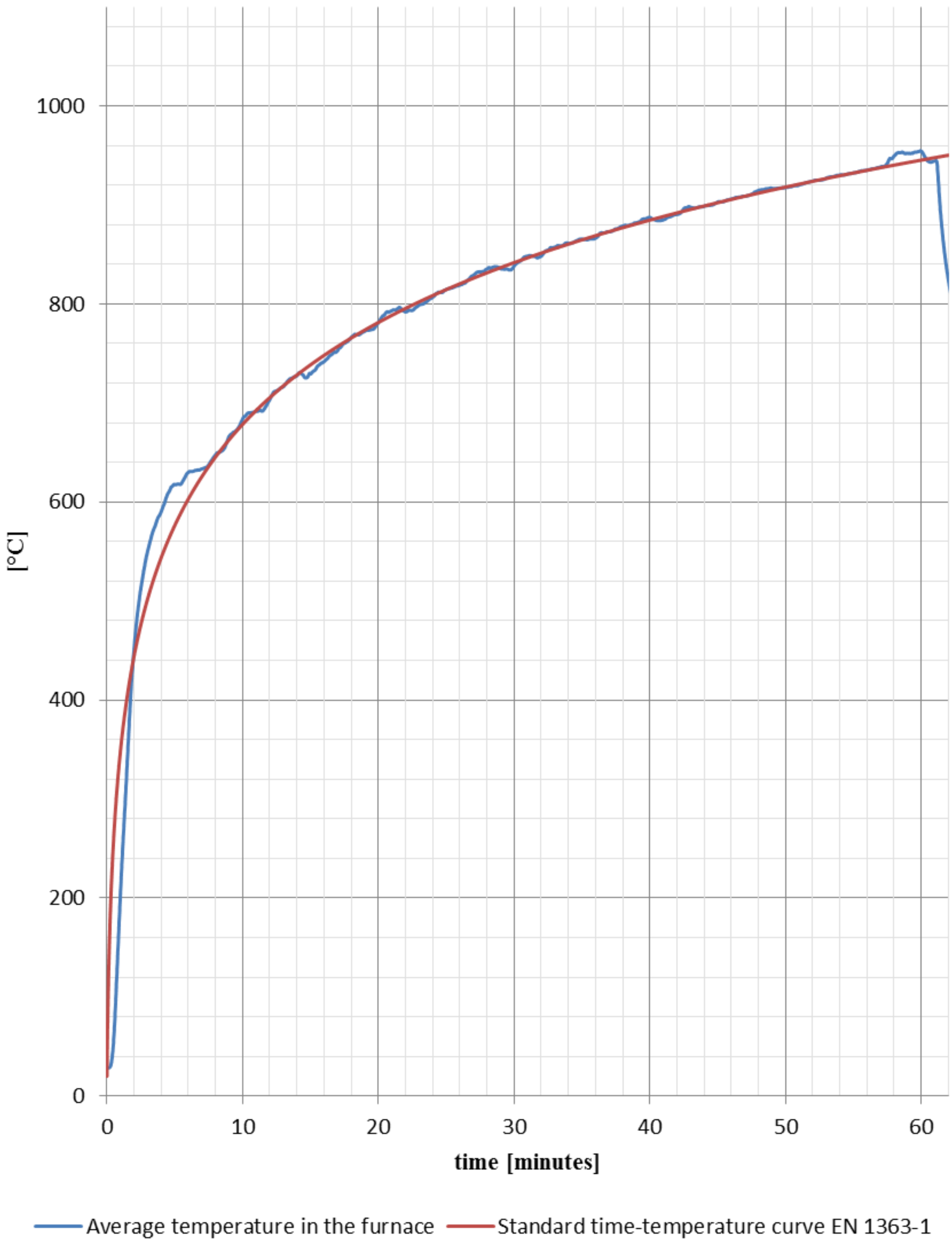

Figure A167. Average temperature in the furnace during the test.

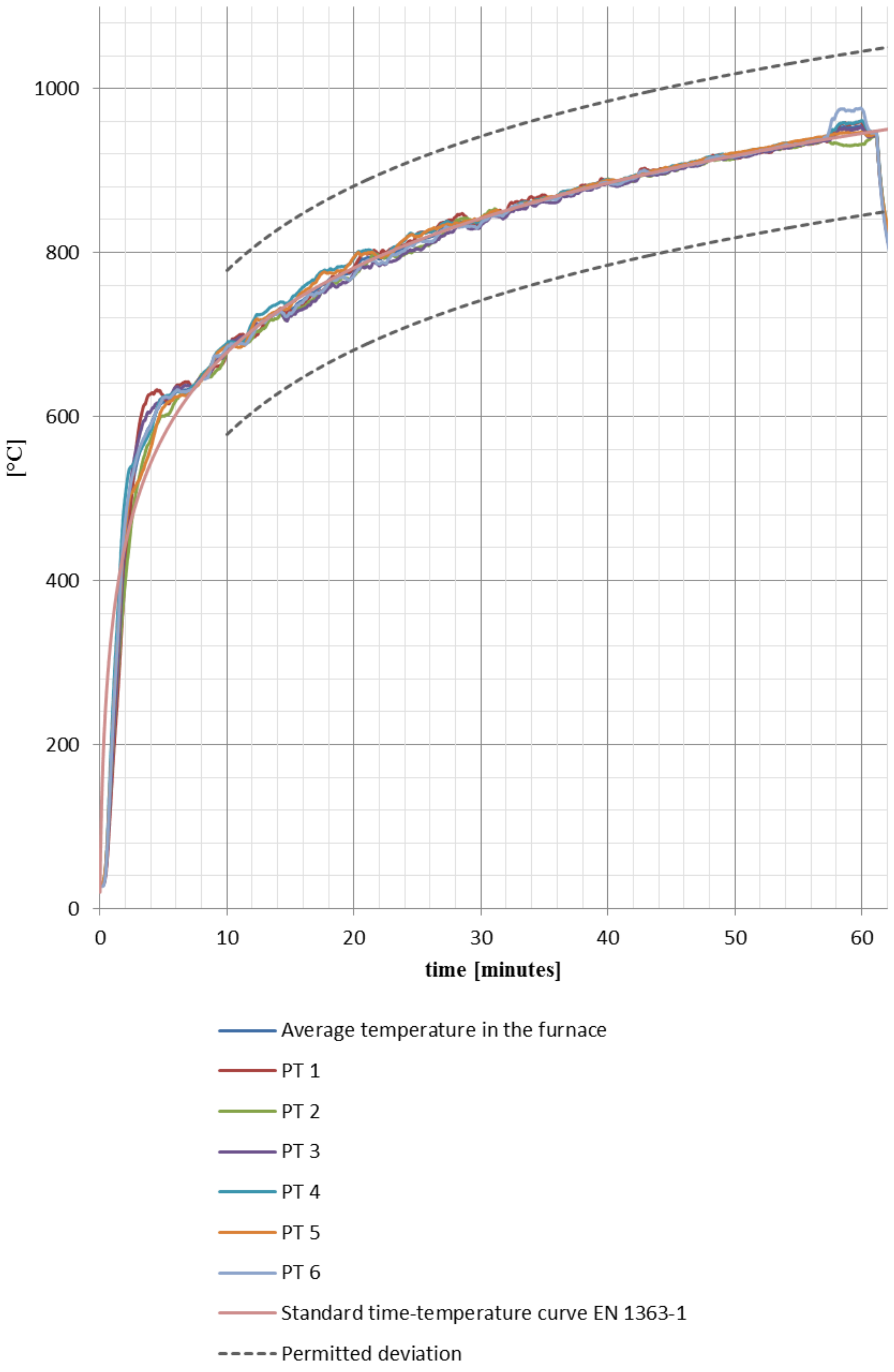

Figure A168. Measured temperatures in the furnace during the test.

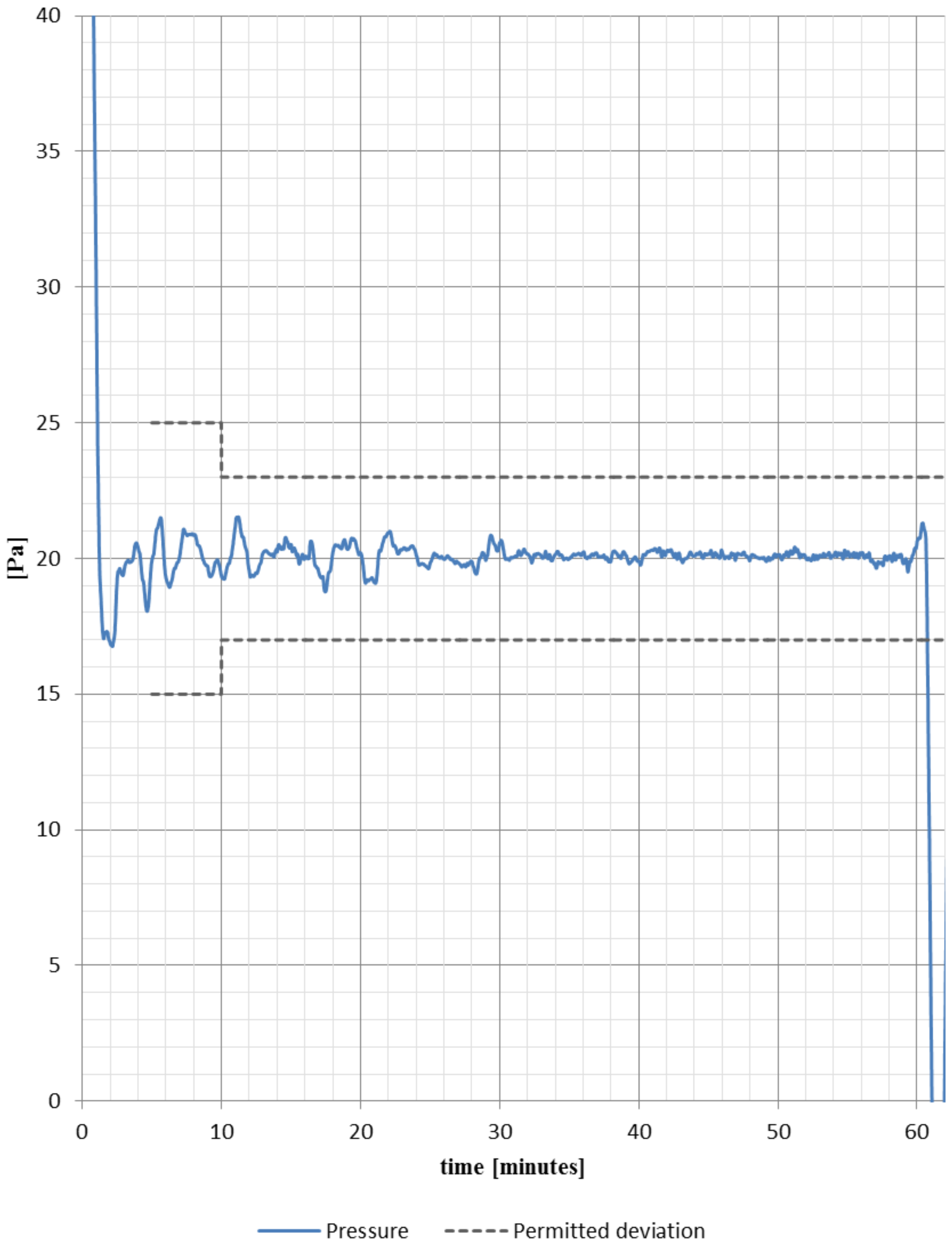

Figure A169. Measured pressure difference between the pressure in the furnace and the ambient pressure during the test.

Large slab, vertical, loaded, 21: 3100x1200-300-Mix 6-0.40-1.0kgPP

The test was performed August 11, 2017.

Time [min:s]	Observations (refer to the non-flame side if nothing else is stated)
00:00	Test starts
22:20	The slab is cracked on the sides. Water is coming out from the cracks.
52:00	Water is coming out from the outer surface of the slab.
61:00	The test is stopped.

The spalling of the slab was measured after the test. The measurements were made at the junction between 1/3 width and at 1/5 height of the slab. The position of maximum spalling depth were also evaluated and measured.

The result from the measurement of spalling is described in the figure below.

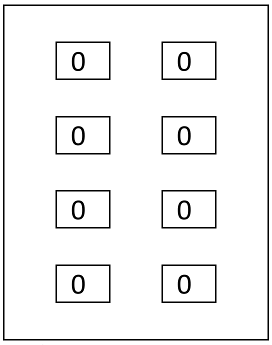

Figure A170. Spalling measurements after the test (mm).

Maximum spalling: 0 mm

The surface of the test sample after the test is show in the photograph below.

Figure A171. Test specimen after the test. No spalling was observed.

The temperature inside the concrete was measured with totally 10 thermocouples placed in two planes parallel to the fire exposed surface. One plane was paced 100 mm in to the concrete and the other was placed 50 mm into the concrete on to the reinforcement net.

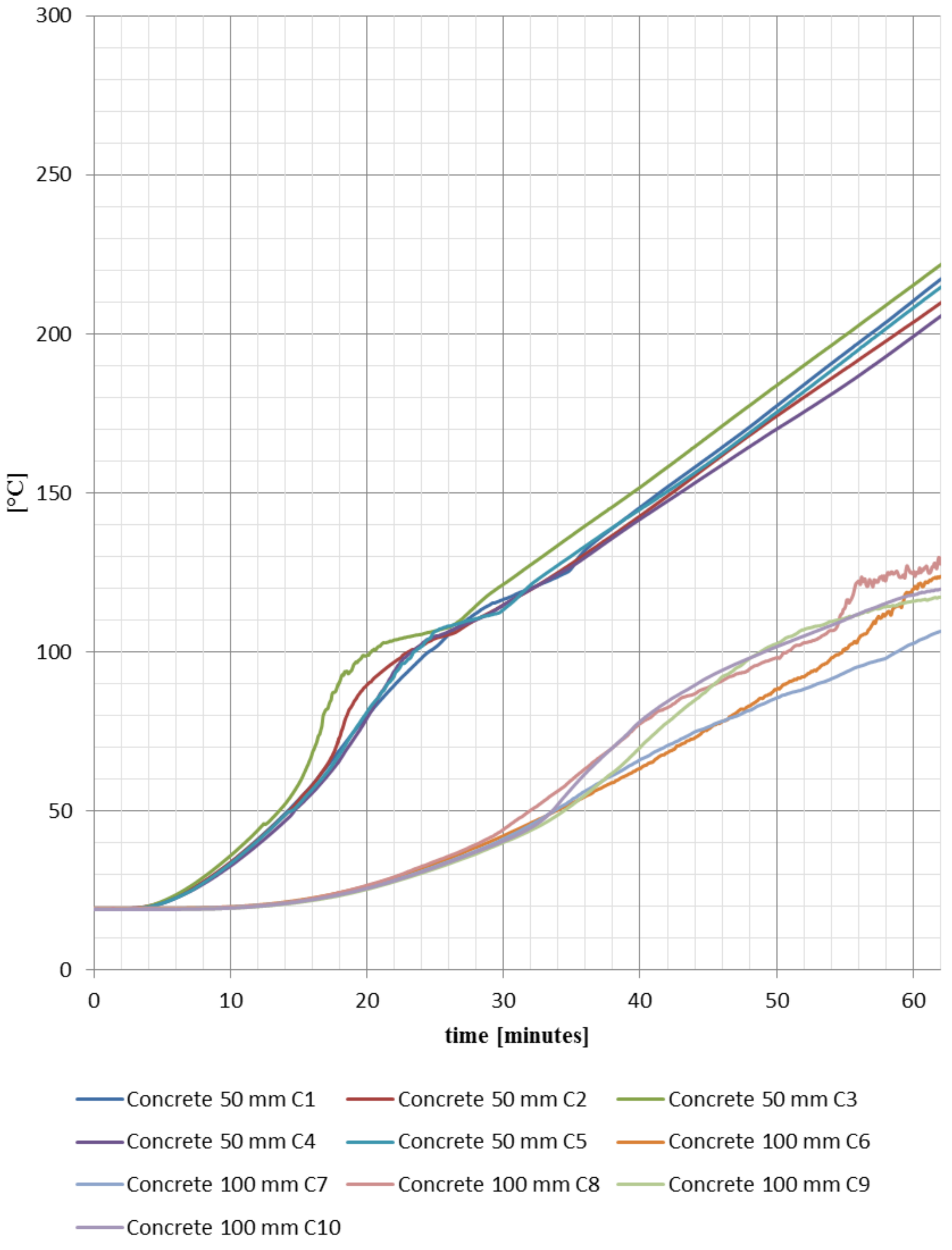

Figure A172. Temperature measured in the concrete during the test.

Figure A173. The test setup at the beginning of the test.


Figure A174. The fire exposed side after 17 minutes of the test.

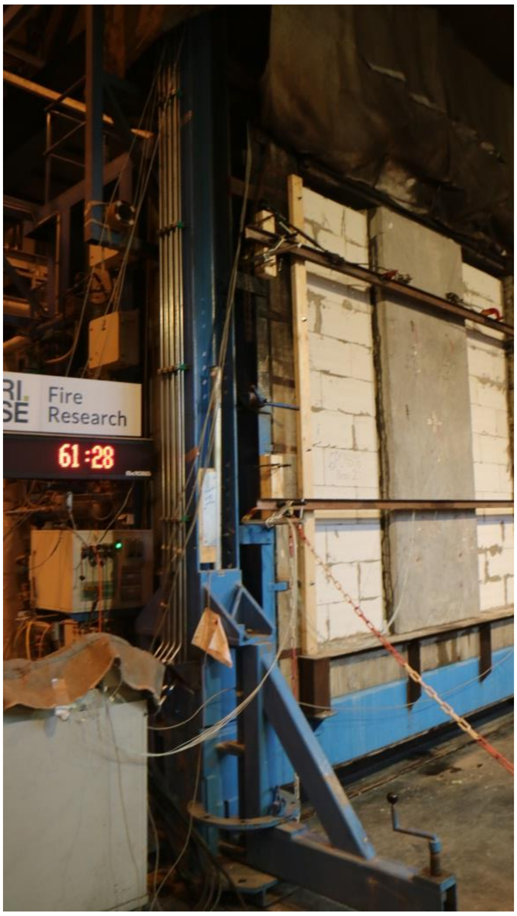

Figure A175. The test setup at the end of the test.

The temperature in the furnace was controlled in accordance with EN 1363-1:2012. The pressure in the furnace was controlled to +20Pa at the top of the test specimen.

The climate in the furnace during the test is described below.

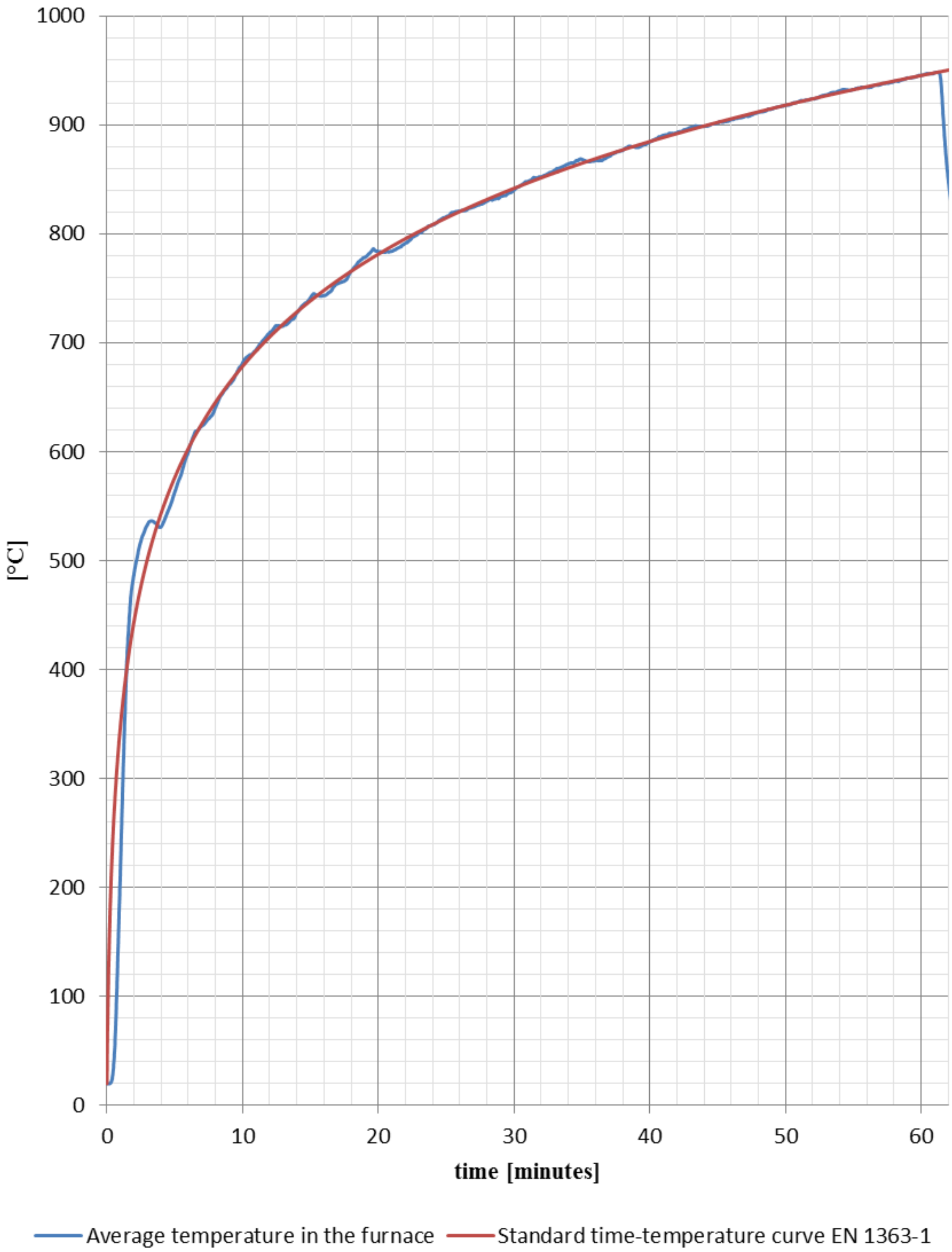

Figure A176. Average temperature in the furnace during the test.

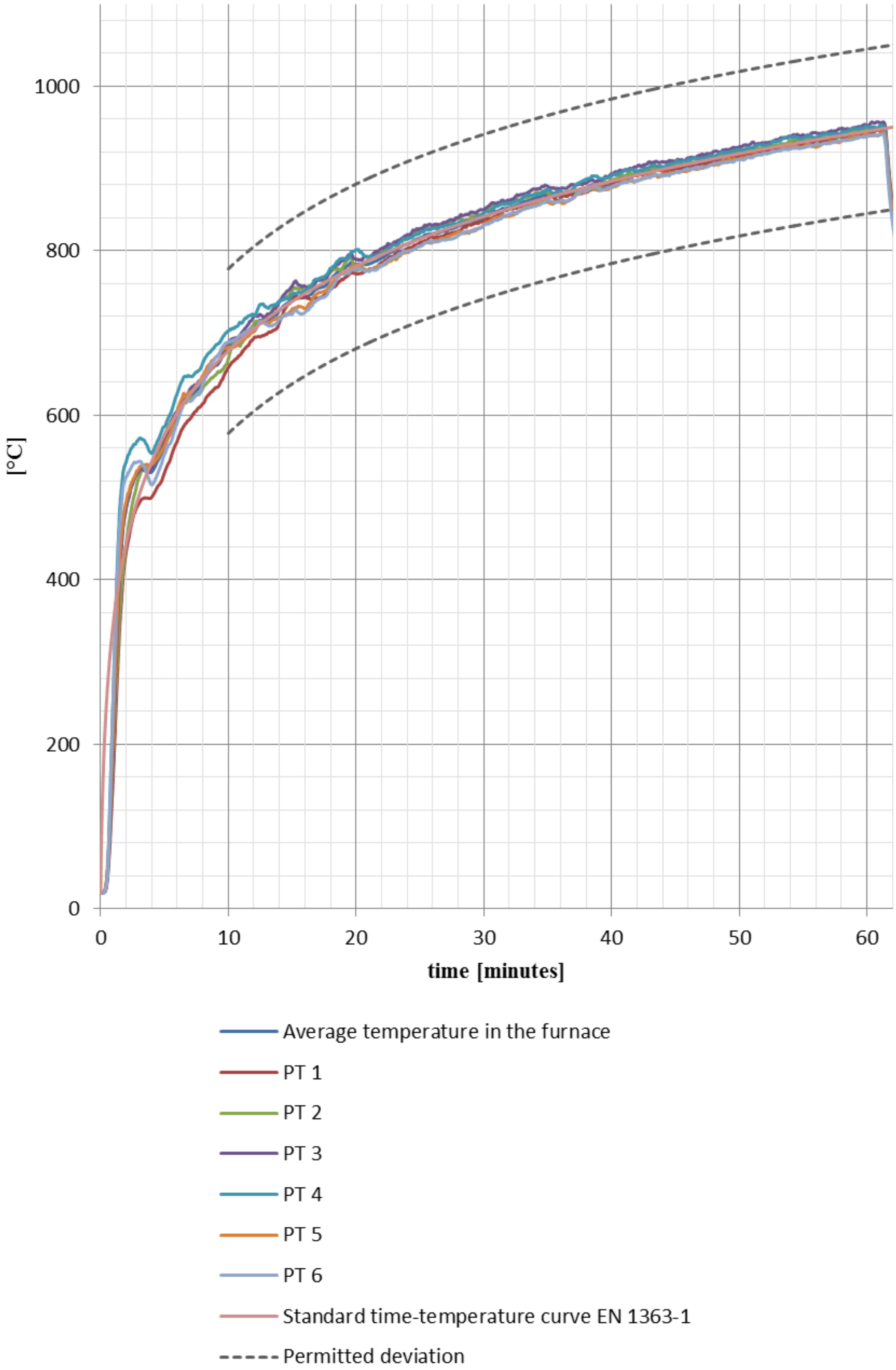

Figure A177. Temperatures measured in the furnace during the test.

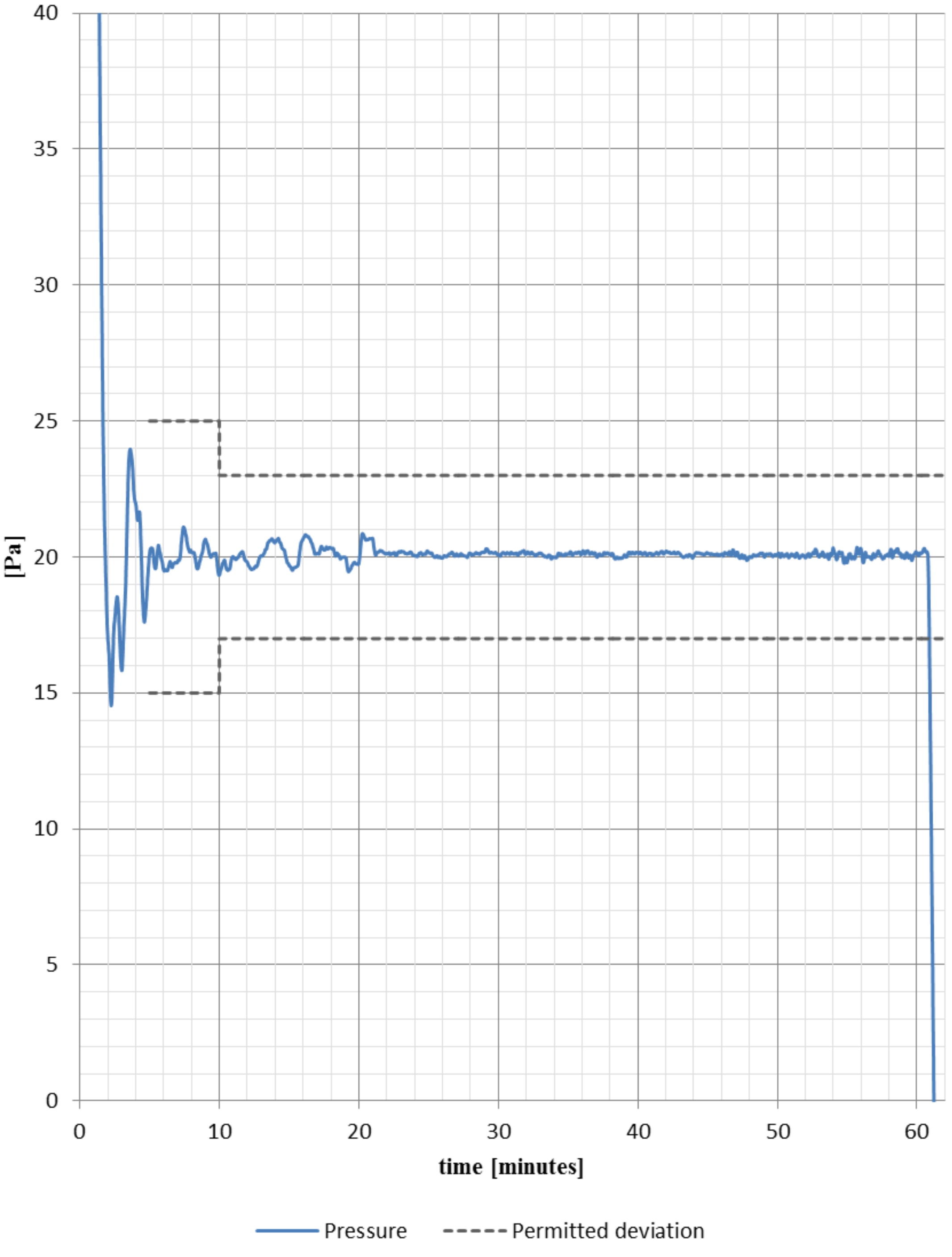

Figure A178. Measured pressure difference between the pressure in the furnace and the ambient pressure during the test.

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