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Measurement of thermal properties at elevated temperatures – Brandforsk project 328-031

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Abstract

An investigation of the TPS (Transient Plane Source) method to determine the thermal properties for building materials at high temperature has been performed. The thermal conductivity, diffusivity and the volumetric specific heat for different building materials at room temperature and at elevated temperatures has been determined. Also influence of moisture content on the thermal properties of a number of materials was instigated.

Key words: Thermal properties, elevated temperatures, transient plane source, TPS, building materials

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Preface

This work was financially supported by the Swedish Board for Fire Research (Brandforsk) as project number 328-031. The work presented in this report has been performed at SP Swedish National Testing and Research Institute who also has contributed financially to the project.

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Summary

An investigation of the TPS (Transient Plane Source) method to determine the thermal properties for materials at high temperature has been performed. The thermal conductivity, thermal diffusivity and the volumetric specific heat for different building materials at room temperature and at elevated temperatures were determined. Also the influence of moisture content on the thermal properties of some materials was investigated.

With the TPS method the thermal conductivity, thermal diffusivity and the volumetric specific heat for isotropic materials can be determined at the same time from a transient measurement, which is a big advantage in comparison with other stationary methods. When measurements with the TPS method are done on anisotropic materials the volumetric specific heat must be known in advance.

The measurements performed on concrete showed a fairly good agreement with previously known values. Also a temperature calculation of the heat transfer inside a fire-exposed concrete slab based on the measured properties corresponded well with the measured values from a real fire test.

Measurements of the thermal properties of insulating materials, wood and wood based products were also performed. The measurements on wood showed fairly comparable results with the Eurocode for the thermal conductivity in the radial direction but a quite big scatter in the measurements was present especially at higher temperatures.

The result from the measurement on high density glass wool seems to be logical but measurements on low weight fibrous materials as low-density glass wool and low-density mineral wool at high temperature were shown to be problematic with the TPS equipment. The illogical jumps in the thermal properties when switching from Kapton insulated sensors (low temperature measurements) to Mica insulated sensors (high temperature measurements) are yet to be explained.

1 Introduction

1.1 Background

During the past decades the use of computer based calculation methods in the field of fire technology has increased. As the accuracy of the models and the field of application for computer-based calculations are broadened it sets new demands of the input parameters. A fundamental factor when dealing with fire related calculations are the thermal properties of the materials. It is often a big discrepancy between these properties at room temperature and at elevated temperatures accomplished in the fire situation. Therefore it is an important task to refine the measurement techniques for these parameters.

The most common way to measure thermal conductivity is by steady state methods. The fundamental of these methods is to achieve a stationary temperature field and to perform a heat flux measurement at the boundary. The steady state methods are typically more time consuming and require bigger test samples then the transient methods. The sheer volume of current materials and their applications combined with the fact that their availability in limited sizes and forms make steady state methods unsuitable for measurement requirements (Tye et al. 2003).

The transient plane source method (TPS) is one of a few methods enabling determination of the thermal conductivity, thermal diffusivity and the specific heat simultaneously. With stationary methods it is not possible to measure time dependent properties.

1.2 Previous studies

1.2.1 Concrete

Determination of the thermal properties of concrete at high temperature is not a new issue. Ödeen and Nordström (1972) performed measurements on concrete at temperatures from room temperature up to 1000 °C. The measurements at high temperature were performed with the Stålhane-Pyk method (thermal conductivity) and a Dynatech calorimeter (specific heat). The thermal conductivity measurements show the typical decay at high temperatures. When the material is cooling after an exposure at high temperature the thermal conductivity is approximately constant, see figure 1.

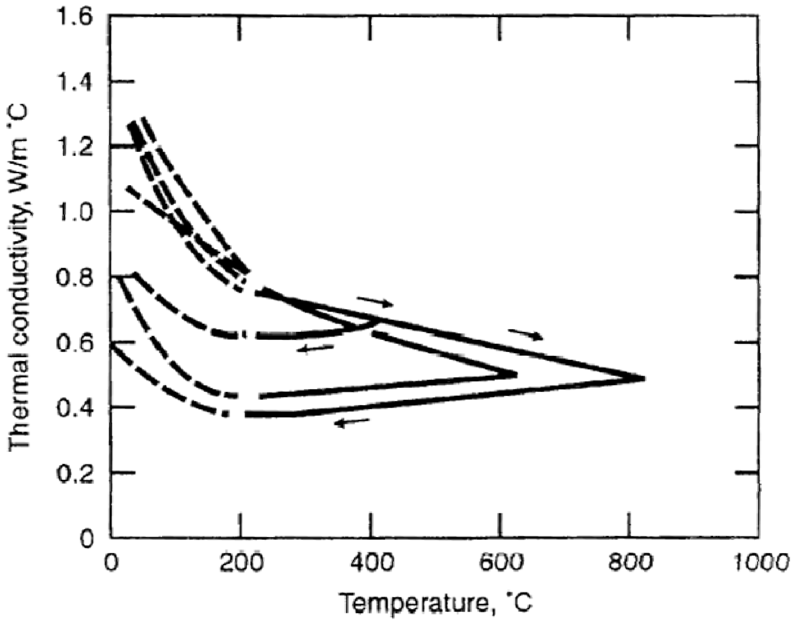


Figure 1. Temperature dependent thermal conductivity for concrete with w/c = 0.7 (Ödeen and Nordström 1972). The cooling phase is included in the diagram.

Concrete is a hygroscopic material, which means that it can contain different amounts of moisture. Morabito (1989) has investigated the moisture dependence of different type of concrete at room temperature, see figure 2. In that study the hot wire method was used, which like the TPS method is a transient method allowing the measurement to be completed before the moisture has time to migrate significantly.

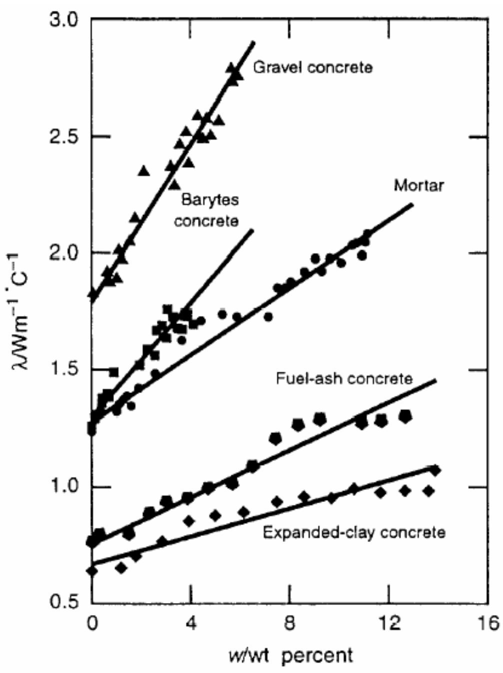


Figure 2. Thermal conductivity versus moisture content of different kind for concrete (Morabito 1989).

When a calculation is to be performed according to the Eurocode, the thermal properties are prescribed. The temperature dependent thermal conductivity and specific heat are stated in the Eurocode 2 part 1-2 (2003). The thermal conductivity is shown as an upper and lower limit curve, see figure 3. According to the standard the thermal conductivity for high performance concrete may be higher than for ordinary concrete. There is a possibility to make national interpretations within the limits. The specific heat for siliceous concrete as a function of temperature is shown in figure 4. Included in the figure is also the latent heat for different moisture contents.

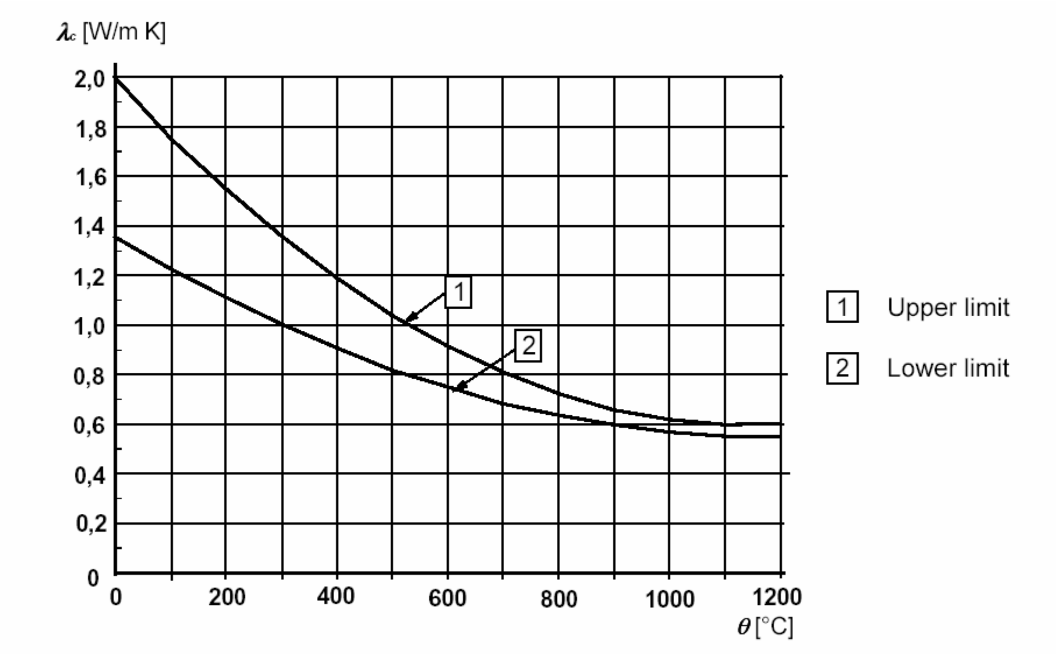


Figure 3. Thermal conductivity of concrete according to Eurocode 2 part 1-2 (2003).

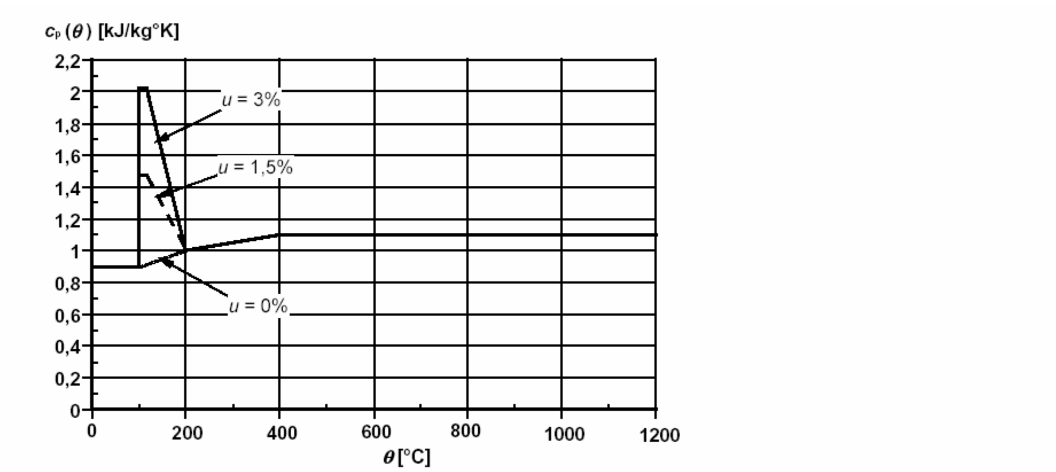


Figure 4. Specific heat for siliceous concrete as a function of temperature at three different moisture contents according to Eurocode 2 part 1-2 (2003).

The variation of the thermal properties between different types of concrete can sometimes be of quite a big magnitude. In figures 5 and 6 measurements from different sources are shown together. One factor causing the variation may be that different methods have been used in the measurements.

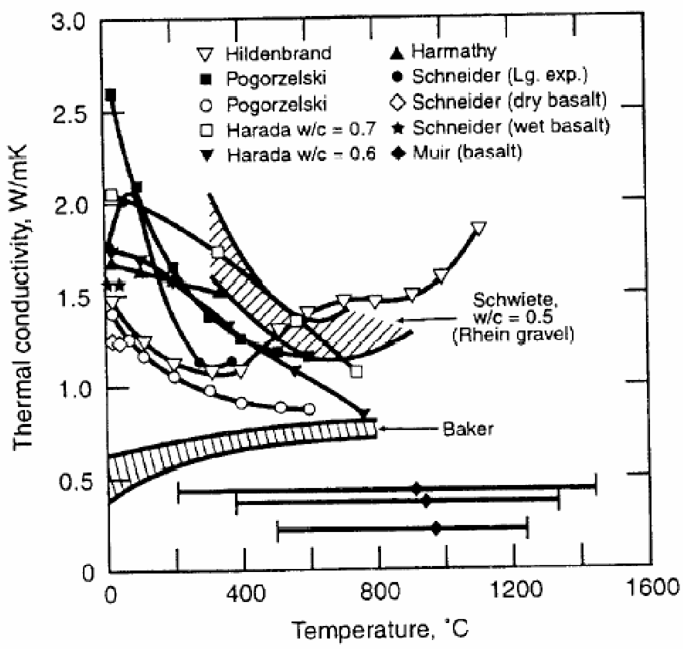


Figure 5. Thermal conductivity of siliceous-aggregate concrete. Compilation made by Schneider (1982).

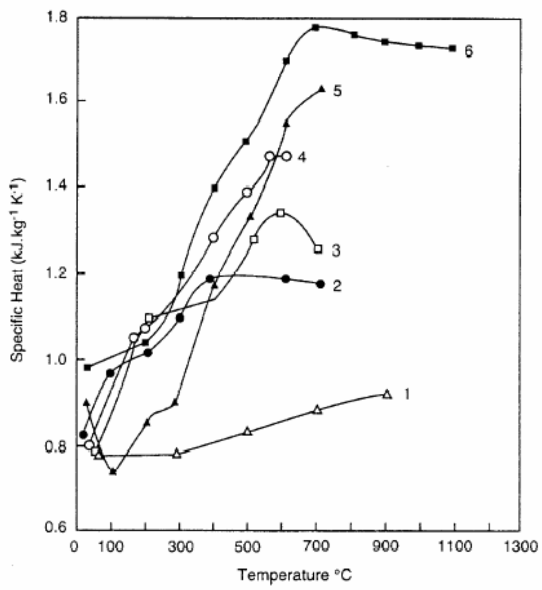


Figure 6. Effect of temperature on measured specific heat of various concretes. Compilation made by Bažant and Kaplan (1996). (1) granite aggregate concrete (Ödeen, 1968); (2) limestone aggregate concrete (Collet and Tavernier, 1976); (3) lime stone aggregate concrete (Harmathy and Allen, 1973); (4) siliceous aggregate concrete (Harmathy and Allen, 1973); (5) limestone aggregate concrete (Hildebrand, et al., 1978); (6) siliceous aggregate concrete (Hildebrand, et al., 1978)

1.2.2 Wood and woodbased materials

Wood and other cellulosic materials have a low thermal conductivity due to the porosity of the material and the absence of free electrons (in opposite to metals). The thermal conductivity varies in different directions of wood. The different directions are shown in figure 7. According to Kollman and Cote (1968) the conductivity in the radial direction is about 5 to 10 % greater then in the tangential direction and the conductivity in longitudinal direction is about 2.25-2.75 times the conductivity across the grain (radial direction). The thermal conductivity as a function of density for wood and fibreboard is shown in figure 8. At NIST (National Institute of Standards and Technology, USA), the result from thermal conductivity measurements on the particleboard was 0.15 W/mK (NIST database). The measurement at NIST was performed with a guarded hot plate at room temperature on a particleboard with a density of 795 kg/m^3.

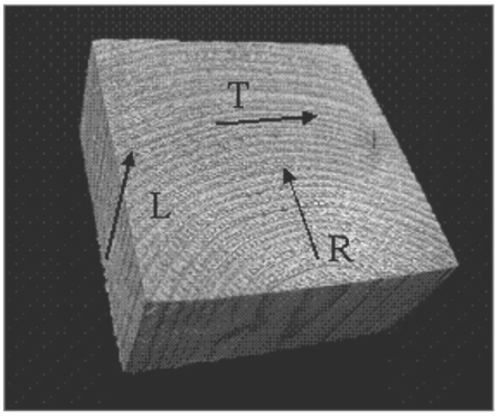


Figure 7. Principle directions in wood: R = Radial, T =Tangential and L =Longitudinal

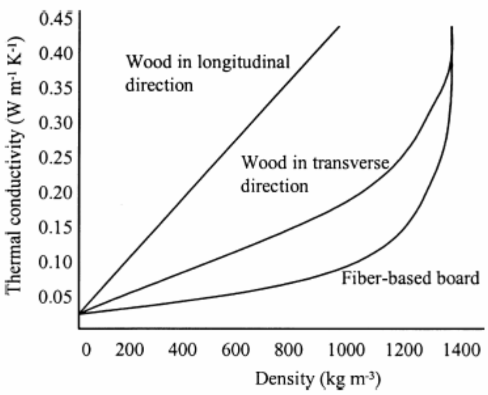


Figure 8. Effect of density on thermal conductivity of wood and fibre-based board at 12 % moisture content and temperature 300 K (Kollman and Cote 1968).

The temperature dependent thermal properties for wood according to Eurocode 5: Part 1-2 (2003) are shown in figures 9 and 10.

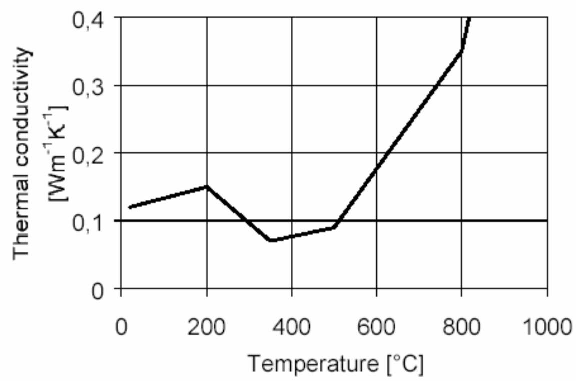


Figure 9. Thermal conductivity for wood and char layer according to Eurocode 5: Part 1-2 (2003).

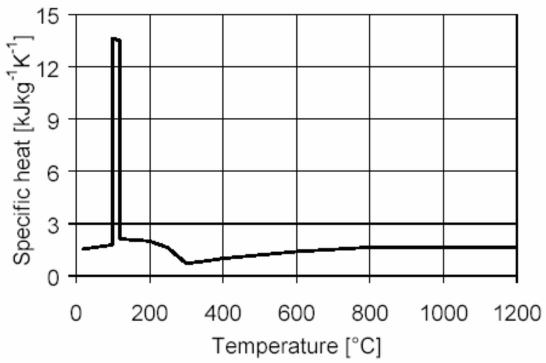


Figure 10. Specific heat for wood and charcoal according to Eurocode 5: Part 1-2 (2003). The peak in the diagram is the latent heat of evaporation.

1.3 Limitations

Due to the nature of the TPS technique no estimation of the internal chemical endothermic or exothermic processes can be done. The measurements performed in this project are in the temperature range 20- 600 °C. With the TPS equipment, measurements can be done up to approximately 750 °C and development is ongoing to expand the range even higher but to save the used equipment the higher limit of the temperatures was set to 600 °C.

The available sensor sizes for this project were Kapton and Mica sensors with radius from 6.403 mm to 9.719 mm. Although in the additional test to check the influence of sensor size, when measurements are performed on concrete, Kapton sensors with the radius 14.61 and 29.52 mm were also used.

Initially some measurements on sealed concrete specimens were to be included in the test program but the high internal pressures associated with that type of testing and the difficult task to find a proper methodology forced us to exclude it from the test program.

In the originally plan only measurements with the basic TPS technique were to be performed on different building materials. But it soon became obvious that in some of the materials the thermal conductivity and thermal diffusivity was direction dependent. Therefore the project was expanded to include anisotropic measurements on wood. When anisotropic measurements are done the volumetric specific heat must be known in advanced.

The intention of this project was not to make a reference work on the thermal properties at high temperature for all building materials. The purpose was to investigate the advantages and eventual disadvantages of using the TPS method for this type of work.

1.4 Objectives

The objective with the study was to examine and develop the TPS technique for measurement of the thermal properties at elevated temperatures for different materials. Within the frame of the project several different building materials were to be studied such as concrete, wood based materials and insulation materials. In addition to the measurements with the TPS method an evaluation of the determined data was to be performed with a comparison between a calculation based on the measured data for concrete and a full-scale fire test.

2 Methodology

2.1 The Transient Plane Source (TPS)

When a measurement according to the basic TPS method is performed a flat round hot disc sensor is placed between two pieces of material, see figure 11. The sensor consists of a thin nickel foil spiral, 10 µm, which is sandwiched between two sheets of electrical insulation material.

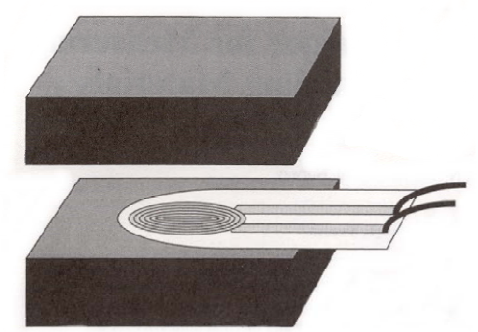


Figure 11. Test setup for a measurement according to the TPS method (Gustafsson and Long 1995).

The hot disc sensor acts as a constant effect generator and a resistance thermometer at the same time. The measurement starts when a stepwise power pulse is applied to the sensor. When a constant electrical effect is applied, the temperature in the censor rises and heat starts to flow to the tested material. The time dependent resistance rise is then recorded and converted with the temperature coefficient of resistivity for Nickel to a temperature response curve, see figure 12.

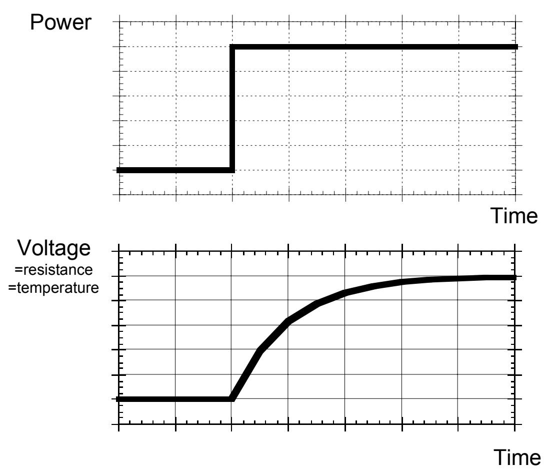


Figure 12. When the stepwise power pulse is applied the change in voltage is recorded and converted to resistance and thereafter temperature.

The temperature rise in the sensor is a direct response of the thermal properties of the tested material. If the material has good insulation properties, which means low conductivity and diffusivity, the temperature of the sensor will rise rapidly when a certain amount of heating effect is applied. If the material on the other hand has good conducting properties the applied heat will be transported faster inside the material and the temperature will not rise as much as in the test of the insulating material.

When measurements are made with the TPS method the test specimen must have a uniform internal temperature distribution. A temperature drift recording, which is the start-up for every measurement, is used to check this. If the temperature recording shows a systematic drift in any direction there is a possibility to compensate for that in the software but the accuracy of the measurement can be reduced considerably and therefore it is not recommended. The measurements at high temperatures in this project have been performed inside a muffle furnace.

2.2 Parameters to set on the instrument

Depending on the thermal properties a proper electrical power, size of sensor and measurement time must be chosen, i.e. it is an iterative process if the properties of the tested material are totally unknown. The power effect selection is direct dependent to the desired temperature rise in the test specimen. For metals a suitable temperature rise is < 1 °C and for insulation materials between approximately 1 and 5 °C. There is a characteristic time for every measurement when the thermal conductivity, thermal diffusivity and the specific heat can be determined from one measurement. This is when the heat profile in the test specimen can be approximated as a mix of the mathematical solutions from a semi-infinite slab and a point source. If the measurement time is to short only the thermal effusivity can be calculated because the mathematical solution approaches the semi-infinite slab case. If the measurement time on the other hand is to long the mathematic solution is more like an infinite solid heated by a constant point source and only the thermal conductivity can be calculated (Gustafson 1991, Gustafsson and Long 1995). A more detailed mathematical description of the used solution strategy in the software is given by Gustafsson (1991).

2.3 Different sensor types

When the temperature is below 500 K, the insulation material of the sensor is Kapton with a thickness of 25 µm and in the 500 – 1000 K range Mica with the thickness of 60 µm is used. The reason for using Nickel as the conducting material in the sensor is because of its large temperature coefficient of resistivity over a big temperature range. The only discontinuity in the temperature coefficient of resistivity for Nickel is around the transition temperature, therefore measurements in the temperature range between 350 and 400 °C are to be avoided (Instruction Manual, 2001). Different sensors are shown in figure 13.

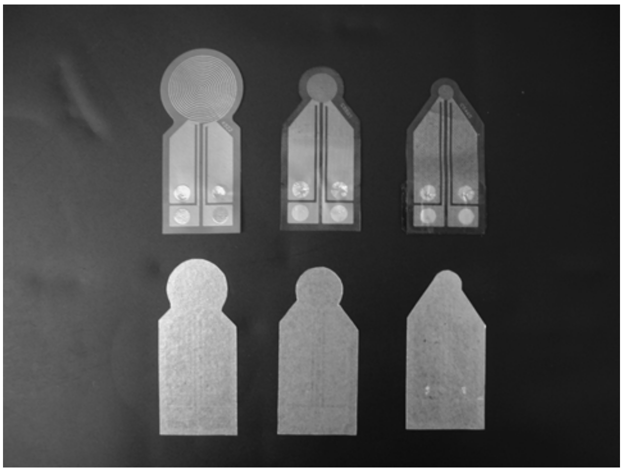


Figure 13. The upper three sensors are insulated with Kapton and the lower three with Mica.

The choice of sensor is mainly dependent on the size of the test specimen. As described in the previous chapter the form of the temperature field inside the specimen should be a mix of a point source and an infinite slab without escaping outwards the specimen. The sensors used in this project can be seen in table 1.

Table 1. Used sensors.

Insulating material in the sensor	Radius [mm]
Kapton	6.403
Mica	6.631
Kapton	9.719
Mica	9.719
Kapton	14.61
Kapton	29.52

2.4 Additional modules

In some materials the thermal conductivity and diffusivity are direction dependent. A variant of the solution algorithm in the TPS software can then be used. But to be able to do the calculation the specific heat of the sample must be known in advance. The solution from the anisotropic module gives the thermal conductivity and diffusivity in the radial and axial directions, see figure 14.

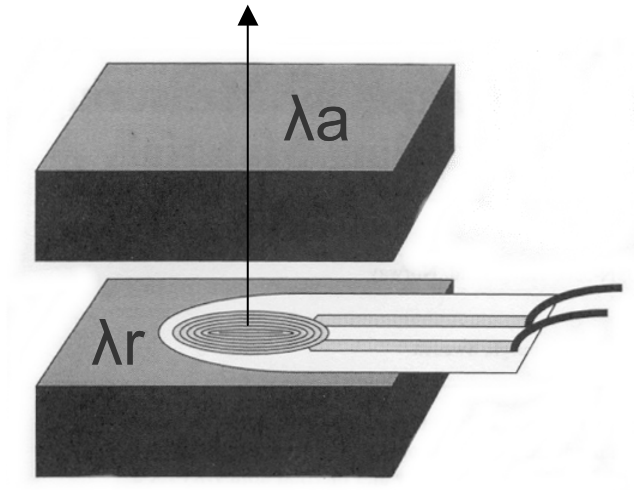


Figure 14. The radial and axial directions in the anisotropic solution in the material in comparison with the sensor position.

A way to determine the specific heat is to use a specially designed specific heat sensor in the TPS package. The sensor is attached to a brass box were a small sample of the material is placed, see figure 15. By a comparison between the thermal response from an empty insulated box and a box containing the test material the actual absorbed energy per degree temperature rise can be recorded and the specific heat can be calculated.

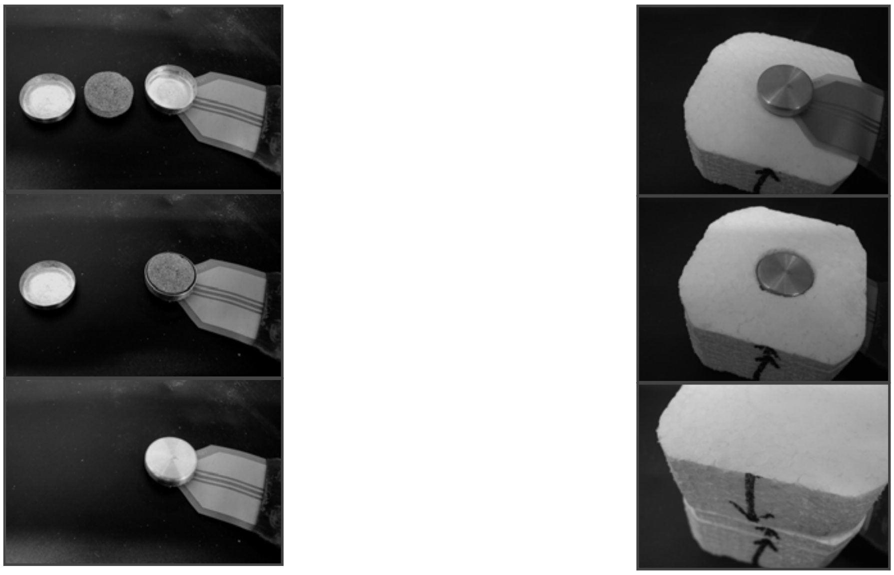


Figure 15. The upper left picture shows the test specimen and the sensor and the down right the whole insulated assembly.

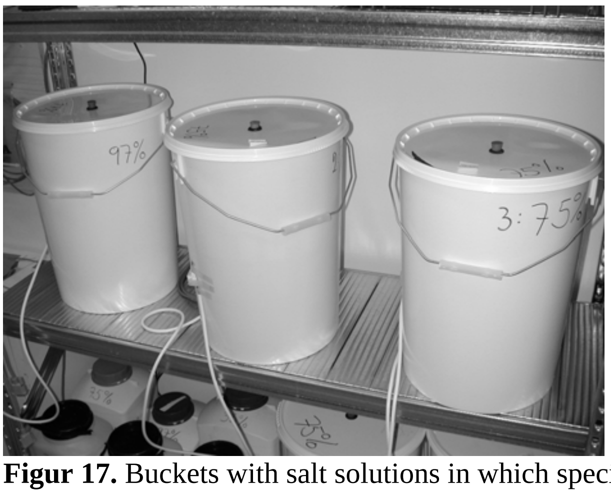
3 Materials

3.1 Conditioning

The thermal properties of porous materials at temperatures below 100 ^{o}C are often dependent of the moisture content of the tested material. Therefore the moisture content is an important parameter when measurements are performed.

A climate room (20 °C, RH 50 %) and buckets containing salt solutions were used to achieve controlled conditioning environments for the test specimens. The salt solutions were placed in the bottoms of airtight plastic buckets, see figures 16-17. To assure that no RH gradients existed in the conditioning buckets fans were used to mix the air inside. The solutions were Magnesium Chloride $MgCl_2$ (RH=33 %), Sodium Chloride NaCl (RH=75%) and Potassium Bisulphate (RH=97 %).

Figur 16. Test specimens stored in a climate room.



Figur 17. Buckets with salt solutions in which specimens were stored.

The complete test program is shown in table 2. The relative humidity values for 90 °C are equilibrium values at room temperature.

Table 2 Test program with TPS.

	20 °C	~90 °C	Elevated temperatures (> 90 °C)
Conventional concrete	0 % RH 33 % RH 50 % RH 75 % RH 97 % RH	0 % RH 33 % RH* 75 % RH* 97 % RH*	0 % RH
Conventional concrete dried at:	200 °C 400 °C 600 °C		
High performance concrete	0 % RH 50 % RH 75 % RH	0 % RH	0 % RH
Self-compacting concrete	0 % RH 75 % RH	0 % RH	0 % RH
Cement paste	0 % RH	0 % RH	0 % RH
Spruce – low density	50 % RH	0 % RH	0 % RH
Spruce- high density	50% RH	0 % RH	0 % RH
Particle board	0 % RH	0 % RH	0 % RH
Fibre board	0 % RH	0 % RH	0 % RH
PMMA (Polymethylmetacrylate)	0 % RH	0 % RH	
Glass wool - density 29 kg/m^3	50 % RH	0 % RH	0 % RH
Glass wool - density 115kg/m^3	50 % RH	0 % RH	0 % RH
Rock wool - density 33 kg/m^3	50 % RH	0 % RH	0 % RH
Polystyrene	50 % RH	0 % RH	
Polyurethane	50 % RH	0 % RH	

* initial RH at room temperature

3.2 Tested materials

3.2.1 Conventional concrete

A total of 38 specimens were manufactured for TPS measurements. The concrete recipe used is shown in table 3. The concrete was casted in cylindrical moulds with a diameter of 70 mm and a length of 500 mm. In addition to the cylinders cubes were casted for measurement of compressive strength. The 28 days strength measured in accordance with SS 13 72 10 as well as the raw density is given in table 4. The slump measurement of the concrete was 50 mm.

The concrete was stored under water until the forms were removed. The cylinders were cut into discs with the thickness 20 mm, two discs for each TPS specimen. Figure 18 show the cutting of a specimen. The specimens were thereafter stored in a climate room or in boxes with a controlled relative humidity until testing.

Table 3. Recipe of conventional concrete.

	Amount (kg/m^3)
Cement (CEM I)	275
Fine gravel 0-8	1015
Coarse gravel 8-16	864
Water	192
w/c-ratio	0.70

Table 4. Compressive strength and density

	Compressive strength (MPa)	Density (kg/m^3)
K30 – 1	38.6	2326
K30 – 2	38.7	2317
K30 – 3	38.2	2347
Mean	38.5	2330
Standard deviation	0.3	15

Figure 18. Manufacturing of specimens.

3.2.2 High performance concrete

A total of 20 specimens were manufactured for TPS measurements. The concrete recipe used is shown in table 5. The concrete was casted in cylindrical moulds with a diameter of 70 mm and a length of 500 mm. In addition to the cylinders cubes were casted for measurement of compressive strength. The 28 days strength measured in accordance with SS 13 72 10 as well as the raw density is given in table 6. The slump measurement of the concrete was 210 mm.

The concrete was stored under water until the forms were removed. The cylinders were cut into discs with the thickness 20 mm, two discs for each TPS specimen. The specimens were thereafter stored in boxes with a controlled relative humidity until testing.

Table 5. Recipe of high performance concrete.

	Amount (kg/m^3)
Cement (CEM II)	465
Fine gravel 0-8	836
Coarse gravel 8-16	942
Silica	35
Plasiticizer SM56	1.5 %
Water	150
w/c-ratio	0.28

Table 6. Compressive strength and density

	Compressive strength (MPa)	Density (kg/m^3)
K100 – 1	114.5	2444
K100 – 2	112.9	2431
K100 – 3	115.3	2431
Mean	114.2	2435
Standard deviation	1.2	8

3.2.3 Self-compacting concrete

A total of 20 specimens for TPS measurements were manufactured. The concrete recipe used is shown in table 7. The concrete was casted in cylindrical moulds with a diameter of 70 mm and a length of 500 mm. In addition to the cylinders cubes were casted for measurement of compressive strength. The 28 days strength measured in accordance with SS 13 72 10 as well as the raw density is given in table 8. The flow slump measurement of the concrete was 670 mm.

The concrete was stored under water until the forms were removed. The cylinders were cut into discs with the thickness 20 mm, two discs for each TPS specimen. The specimens were thereafter stored in boxes with a controlled relative humidity until testing.

Table 7. Recipe of self-compacting concrete.

	Amount (kg/m^3)
Cement (CEM II)	430
Fine gravel 0-8	1052
Coarse gravel 8-16	635
Limestone filler	127
Plasiticizer SM56	1.0 %
Plasiticizer SM56	1.0 %
Water	164
w/c-ratio	0.38

Table 8. Compressive strength and density

	Compressive strength (MPa)	Density (kg/m^3)
SCC – 1	91.7	2421
SCC – 2	91.8	2423
SCC – 3	93.4	2422
Mean	92.3	2422
Standard deviation	1.0	1

3.2.4 Cement paste

A total of 8 specimens for TPS measurements were manufactured. The recipe used is shown in table 9. The cement paste was casted in cylindrical moulds with a diameter of 70 mm and a length of 500 mm.

The cement paste was stored under water until the forms were removed. The cylinders were cut into discs with the thickness 20 mm, two matched discs for each TPS specimen. The specimens were thereafter stored in a room with the relative humidity 50% and temperature 20 °C until testing.

Table 9. Recipe of cement paste.

	Amount (kg/m^3)
Cement (CEM I)	1374
Water	557
w/c-ratio	0.405

3.3 Wood and wood based materials

3.3.1 Spruce

Spruce timber from south-western Sweden was selected. Two different densities of spruce were used for manufacturing of specimens, one with the density approximately 400 kg/m^3 and one with approximately 600 kg/m^3. A total of 60 specimens were manufactured for TPS measurements. The specimens had dimensions) of 60 x 60 x 30 mm^3 (width x length x height). Matched pairs were used as TPS specimens.

Due to the orthotropic behaviour of wood, specimens were manufactured in such way that the thermal properties could be determined in the three main axis of the material, radial (R), tangential (T) and longitudinal (L).

3.3.2 Particleboard and low density fibreboard

Particleboard and fibreboard are not like ordinary wood orthotropic or anisotropic (in normal scale) so the standard module for TPS measurement can be used to determine the thermal properties. The densities of the particleboard and low-density fibreboard were 595 kg/m^3 and 278 kg/m^3 respectively. The two materials were tested at 0 and 7% moisture content.

3.4 Insulation materials

The type of materials and the density of the different insulation materials are shown in table 10.

Table 10. Some different insulation materials were incorporated in the test series.

Material	Density (kg/m^3)
Polystyrene	18
Flexible polyurethane foam	24
Glass wool (low dens)	29
Glass wool B (high dens)	115
Rock wool (low dens)	33

3.5 Polymethylmetacrylate (PMMA)

Polymethylmetacrylate with a density of 1176 kg/m^3 was tested. PMMA is not actually a building material but was incorporated in the test series anyway.

4 Measurements

4.1 Methodology

The test program was designed to investigate the temperature dependent thermal properties and also in some materials the influence of the moisture content on the properties.

When measurements at temperatures over the room temperature were performed the specimen holder and the specimen were placed inside one of two available muffle furnaces, see figure 19. As seen in figure 20, two test specimens could be placed in the oven at the same time. The temperature in the furnace was measured with an additional thermocouple.

Figure 19. Ovens used for heating the specimens.

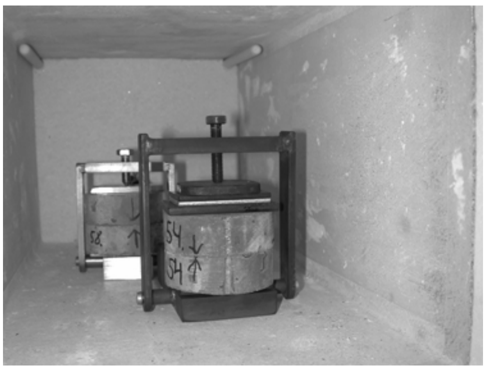


Figure 20. Two test specimens placed inside a test furnace.

The presented measurement values are mean values of at least three measurements with the same test setup and boundary conditions. This is to ensure that no systematic drift is present. Between the measurements the test specimen must go back to thermal equilibrium with the surrounding i.e. no thermal gradients in the material shall be present. If, for example, a test on wood has been performed at the temperature 90 °C the temperature in the centre of the specimen may have risen to 92 °C after the transient measurement and needs to decrease back to 90 °C before next measurement.

To ensure that the sensor is placed in a proper way the test specimen and the sensor are hold in place by a sample holder, see figure 21.

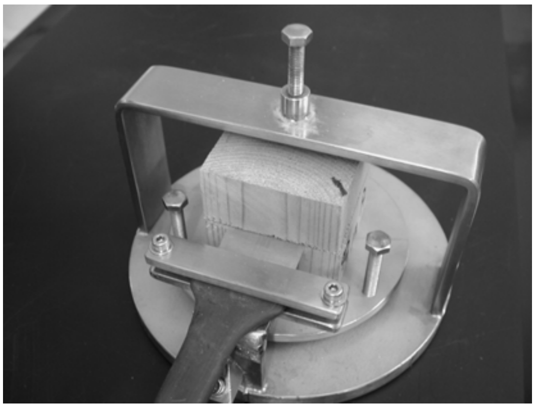


Figure 21. The test setup with a wood test specimen and sample holder for a measurement at room temperature.

At the start of the project only the original TPS module for determination of the thermal properties in isotropic materials was available. But during the project it becomes obvious that the thermal conductivity and diffusivity in wood was heavy direction dependent and therefore the anisotropic module was purchased.

4.2 Concrete

Intentionally, measurements of the thermal properties at high temperatures with different moisture contents were to be performed. But to investigate the partly saturated state of the pores inside the concrete at high temperatures and pressure that can occur during a fire the specimen must be kept inside some kind of pressure chamber. This was shown to be a to challenging task for this project so only measurements at room temperature and 90 °C were performed at different moisture levels.

4.3 Wood

High and low density spruce were tested with the anisotropy TPS module. When this kind of measurements is performed the specific heat must be known in advance. The specific heat for room temperature was measured with the TPS specific heat module and the values at higher temperatures was taken from Eurocode 5: Part 1-2 (2003).

4.4 Insulation materials

The measurements done on insulating materials were performed with the standard module of the TPS package. By using the standard module the thermal properties are assumed to be uniform in all directions. This is true for polystyrene and polyurethane but the fibre insulation materials are more or less orthotropic, see the discussion in chapter 5.9.3.

5 Test procedure and results

5.1 Conventional concrete

Concrete is a non-homogenous material since it contains aggregate and cement paste with different thermal properties. During the measurement series we become suspicious that the size of the available sensor was too small i.e. the volume that is heated during a test is not representative for the material. This suspicion was based on the jump in the results when the sensor was switched from a Kapton insulated sensor with the radius 9.719 mm at 90 °C to a Mica insulated sensor with the radius 6.631 mm at 110 °C for high performance concrete and self-compacting concrete. This jump in results was not present when the same switch was done to a 9.719 mm Kapton insulated sensor. Also when the measurement was performed on a homogenous material (cement paste) the jump in results when switching between a 9.719 mm Kapton and a 6.631 mm Mica sensor was not present.

To get an indication of the size of this variation for different sensor sizes a test was performed in room temperature on a 150 x 150 mm^2 cube sliced in two halves, see results in figure 22. Sensors with the diameter 6.631, 9.719, 14.61 and 29.52 mm were tested. Each dot in the diagram is a mean value of at least three measurements in the same position. The sensor was then moved and by using this method the sensitivity of the sensor for non-homogeneities in the material was checked. The measurements show that the 6.631 mm sensor was a not so good choice, which was suspected. To get a better mean value or more representative value of the thermal properties for concrete a sensor with the diameter of 3 times the biggest aggregate size is recommended. In this case, with 16 mm aggregate, a sensor with a radius of 24 mm would have been a good choice. This also means that the radius of the test specimens ought to be about 100 mm and the thickness at least 48 mm to get a relevant size of the temperature field.

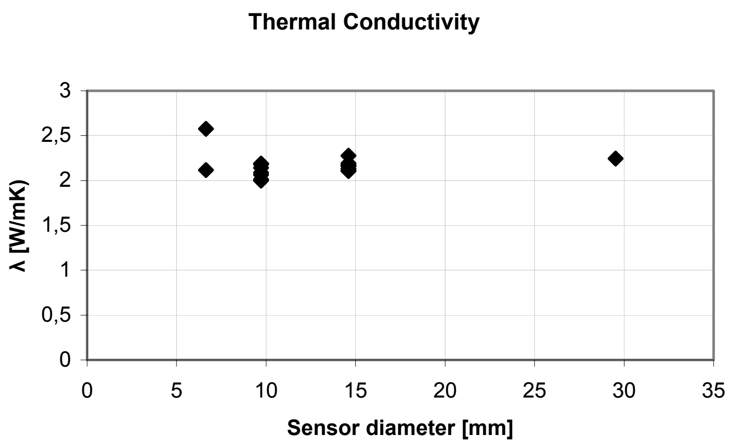


Figure 22. The diagram shows measurements on the same test specimen with different sensors and positions.

5.1.1 Effect of temperature

The effect of temperature on the thermal properties was investigated by a stepwise rise of the temperature and measurements were done when the test specimen had reached thermal equilibrium with the furnace at the desired temperatures. The TPS measurements shown in figure 23 show the typical decay of the thermal conductivity at high temperatures. Specimen No 37 was dried prior the test and specimen 23 was in equilibrium with 33 % RH at room temperature. The results from the conductivity measurements done on specimen 23 are suspicious high. This can be due to the sensor problem described in the previous chapter. The decline of the thermal diffusivity with temperature is shown in figure 24 and the slightly rise of the specific heat with temperature is shown in figure 25.

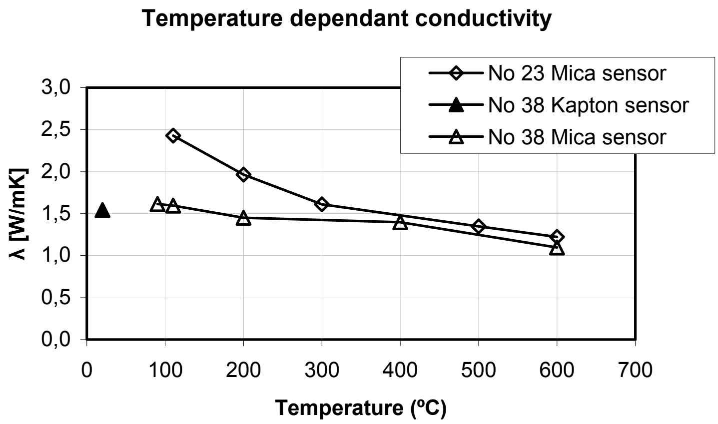


Figure 23. The temperature dependent thermal conductivity for conventional concrete. The sensor radius was 9.719 mm for both the used Kapton and Mica sensors. Specimen No 23 were in equilibrium with 33% RH prior test and No 38 was dried before the test.

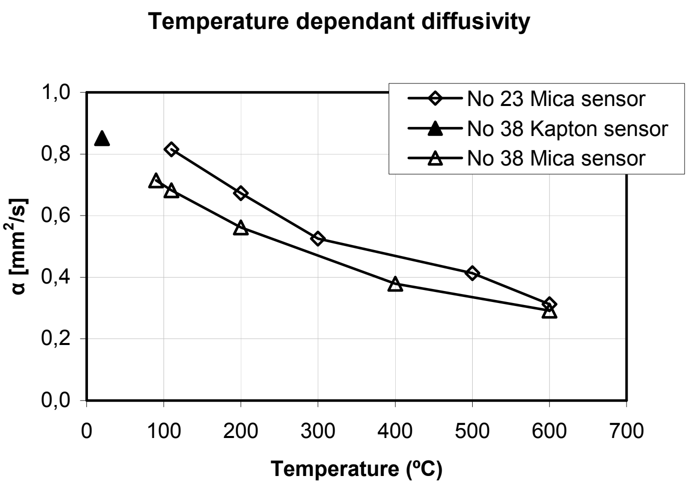


Figure 24. The temperature dependant thermal diffusivity for conventional concrete.

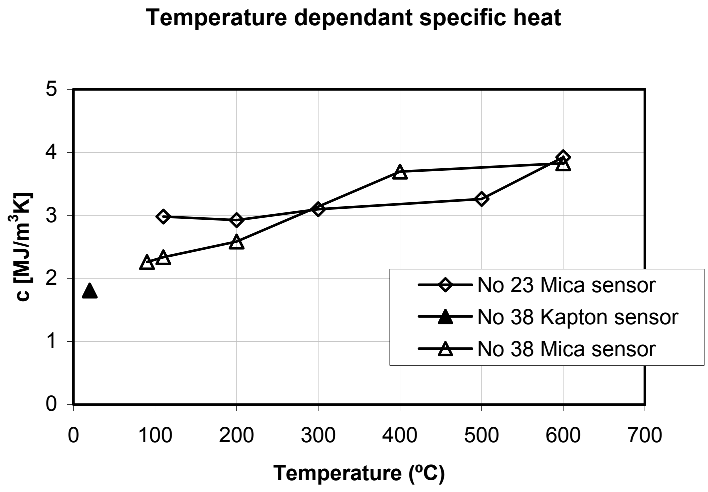


Figure 25. The temperature dependent specific heat for conventional concrete.

5.1.2 Effect of moisture content

The effect of the moisture content was investigated by tests on specimens conditioned in different climates prior the test. After the test the specimens were dried at 105 °C. The relation between relative humidity and moisture content is shown in figure 26.

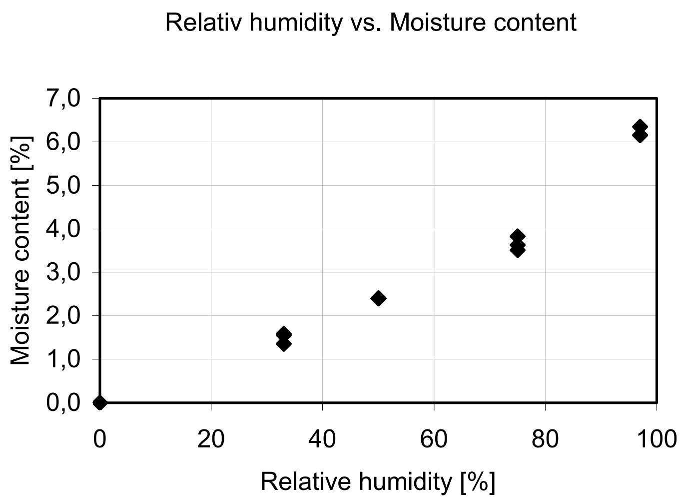


Figure 26. The relation between relative humidity and moisture content for the conventional concrete specimens.

When the relative humidity in conventional concrete is increased also the thermal conductivity and specific heat is increasing. This relationship is shown in figures 27-28 and 31-32. The effect is not so pronounced at 90 °C as in room temperature.

The moisture effect on the thermal diffusivity, figures 29-30, is small.

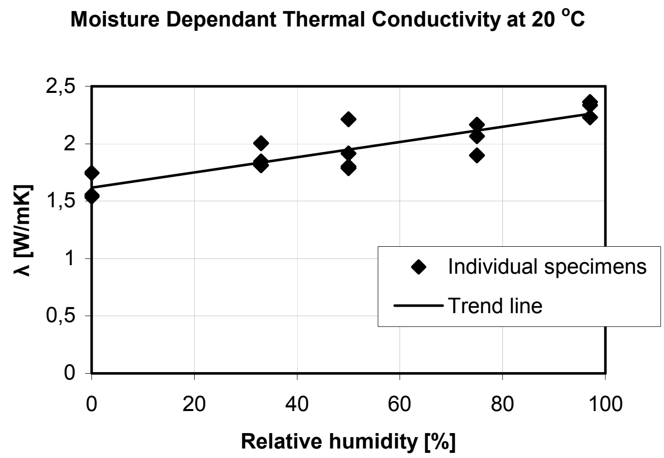


Figure 27. The moisture dependent thermal conductivity for conventional concrete at 20 °C. Test specimens conditioned at different relative humidity.

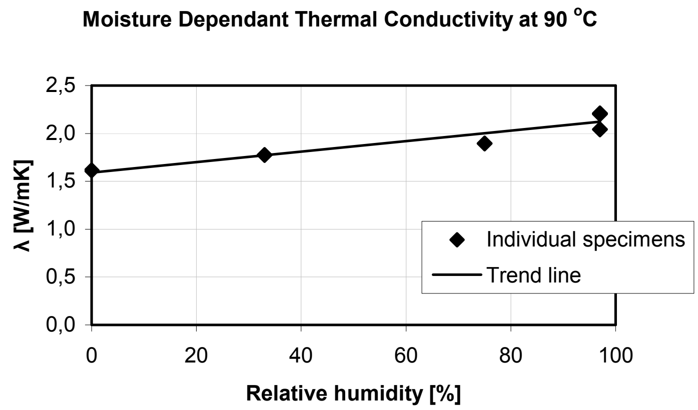


Figure 28. The moisture dependent thermal conductivity for conventional concrete at 90 °C. The relative humidity on the x –axis is at room temperature prior the testing.

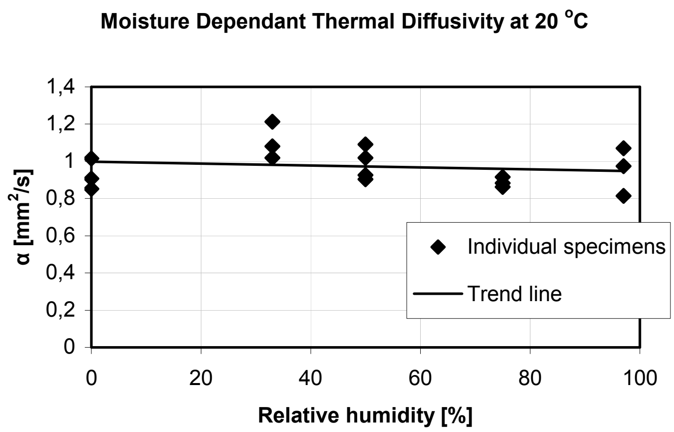


Figure 29. The moisture dependent thermal diffusivity for conventional concrete at 20 °C.

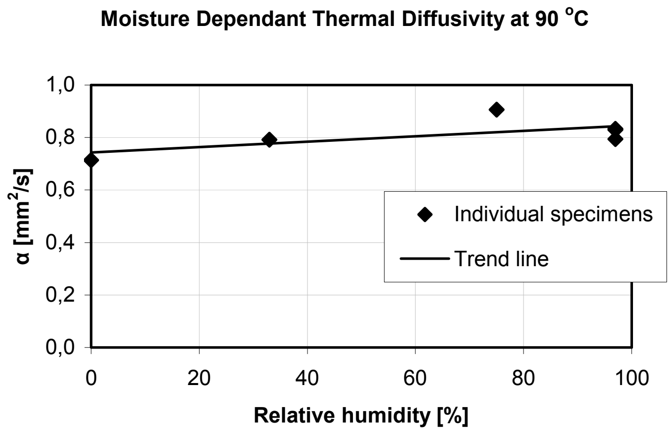


Figure 30. The moisture dependent thermal diffusivity for conventional concrete at 90 °C. The relative humidity on the x –axis is at room temperature prior the testing.

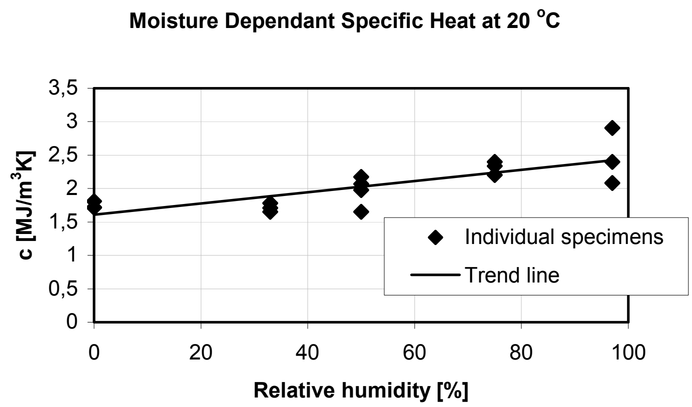


Figure 31. The moisture dependent specific heat for conventional concrete at 20 °C.

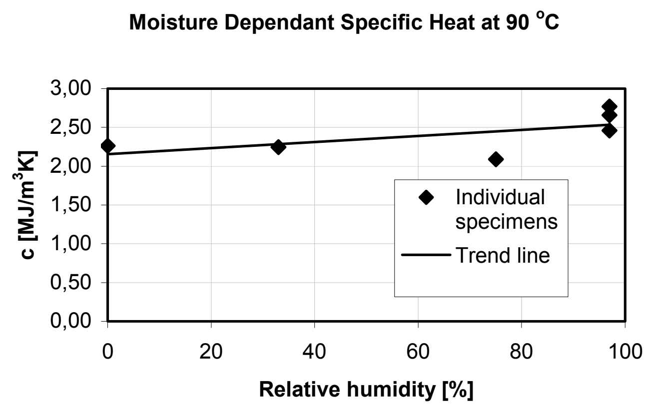


Figure 32. The moisture dependent specific heat for conventional concrete at 90 °C. The relative humidity on the x –axis is at room temperature prior the testing.

5.1.3 Residual values after drying

The purpose of these tests was to investigate if the measurement of residual values after drying could be a way to determine the thermal properties at high temperature. The assumption is based on that the thermal properties are almost stable during the cooling phase.

The thermal properties of concrete specimens dried at 105 °C were tested at room temperature and then tested again at room temperature after drying at three different temperatures namely 200, 400 and 600 °C.

Table 11-13 shows the residual values for ordinary concrete.

Table 11 A concrete specimen tested at room temperature after drying at 105 °C and then tested again after drying at 200 °C.

Drying temperature	Conductivity (W/mK)	Diffusivity (mm^2/s)	Specific heat (MJ/m^3K)
105 ºC	1.60	1.02	1.58
200 ºC	1.55	1.04	1.49
Diff in %	-4	2	-5

Table 12 A concrete specimen tested at room temperature after drying at 105 ºC and then tested again after drying at 400 ºC.

Drying temperature	Conductivity (W/mK)	Diffusivity (mm^2/s)	Specific heat (MJ/m^3K)
105 ºC	1.65	0.96	1.72
400 ºC	1.46	0.78	1.87
Diff in %	-12	-19	9

Table 13 A concrete specimen tested at room temperature after drying at 105 ºC and then tested again after drying at 600 ºC.

Drying temperature	Conductivity (W/mK)	Diffusivity (mm^2/s)	Specific heat (MJ/m^3K)
105 ºC	1.97	0.89	2.21
600 ºC	1.18	0.57	2.08
Diff in %	-40	-37	-6

The results from the measurements of the residual thermal proprieties on concrete dried at 200, 400 and 600 °C may be an indirect way to determine the properties at high temperature. But this methodology must be further investigated with bigger sensors as discussed a previous chapter.

5.2 High performance concrete

5.2.1 Effect of temperature

As shown in figure 33 there is a big discrepancy in the result of the measurement between 90 and 110 °C. The reason for that is supposed to be the switch from a radius 9.719 mm Kapton to a radius 6.631 mm Mica sensor. The same phenomenon was present on one of the test specimens when the same sensor switch was performed in the measurement on self-compacting concrete but not for conventional concrete when the switch was from a radius 9.719 mm Kapton to a radius 9.719 mm Mica sensor. After these measurements the influence of sensor radius was investigated further, see chapter 5.1.

Figures 34 and 35 shows the thermal diffusivity and specific heat respectively. The large jump due to the sensor switch is present in the specific heat measurement but not in the thermal diffusivity measurement.

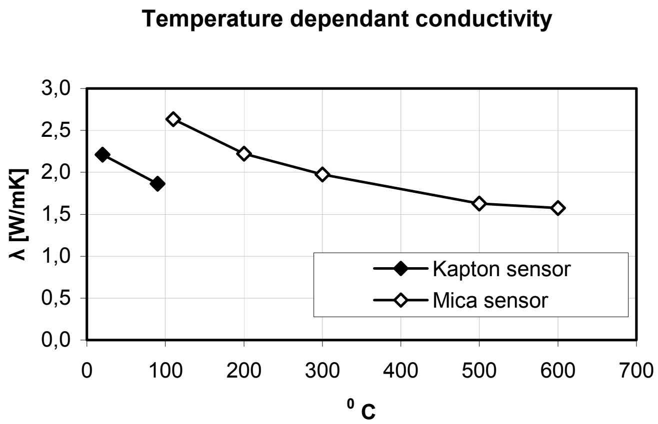


Figure 33. The temperature dependent thermal conductivity for high performance concrete. The discrepancy in conductivity is when the sensor was switched from a radius 9.719 mm Kapton to a radius 6.631 mm Mica. The test specimen was dried before the test.

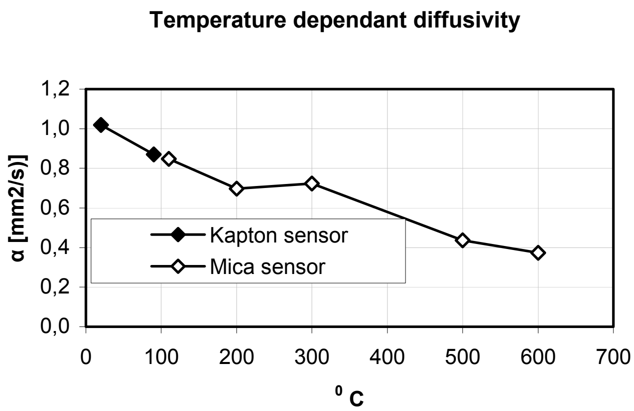


Figure 34. The temperature dependent thermal diffusivity for high performance concrete.

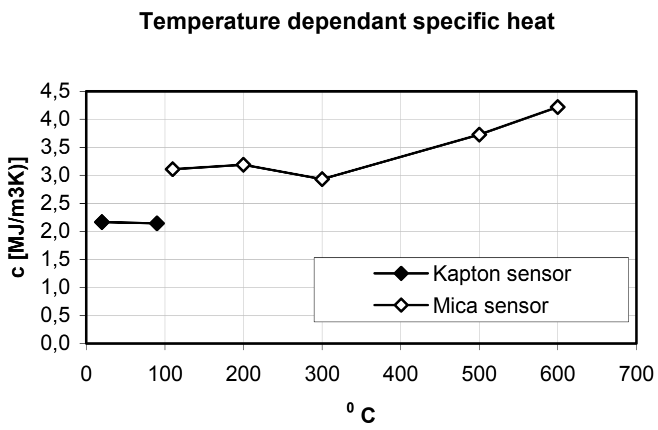


Figure 35. The temperature dependent specific heat for high performance concrete. The discrepancy in specific heat is when the sensor was switched from a radius 9.719 mm Kapton to a radius 6.631 mm Mica.

5.2.2 Effect of moisture content

The influence of the moisture on the thermal properties seems to be smaller for high performance concrete then for conventional concrete, see figures 36-38.

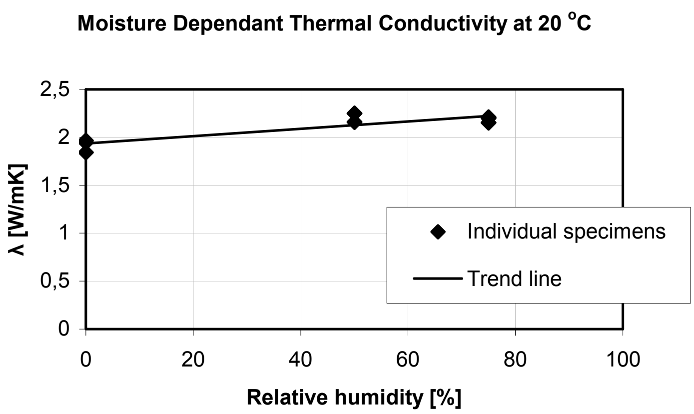


Figure 36. The moisture dependent thermal conductivity for high performance concrete at 20 °C. The trend line in the diagram is a coarse assumption but it may give an indication of the difference.

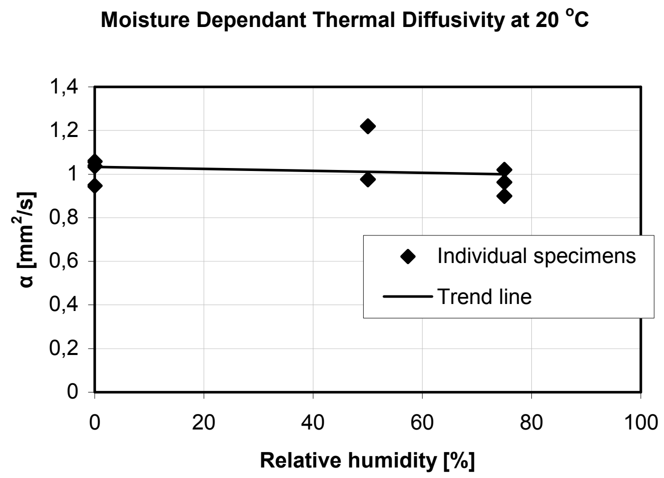


Figure 37. The moisture dependent thermal diffusivity for high performance concrete at 20 °C. The trend line in the diagram is a coarse assumption but it may give an indication of the difference.

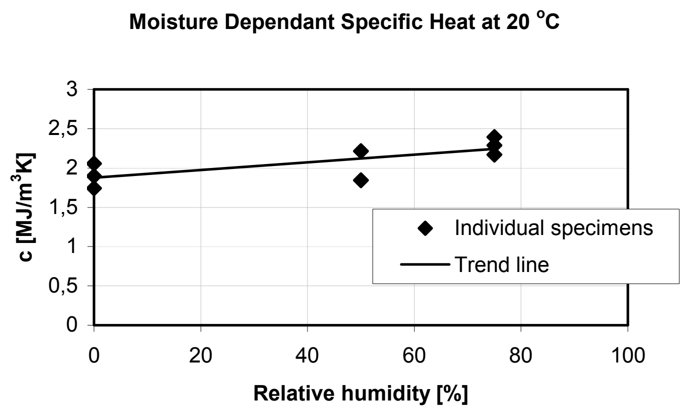


Figure 38. The moisture dependent specific heat for high performance concrete at 20 °C. The trend line in the diagram is a coarse assumption but it may give an indication of the difference.

5.3 Self-compacting concrete

5.3.1 Effect of temperature

As shown in figure 39 there is a discrepancy in the result of the measurement for test specimen No. 69 between 90 and 110 °C. The reason for that is supposed to be the switch from from a radius 9.719 mm Kapton to a radius 6.631 mm Mica sensor, see discussion in chapter 5.1. Test specimen No. 69 was dried after the test at room temperature and specimen No. 75 was dried prior the testing.

Figure 40 and 41 shows the thermal diffusivity and specific heat respectively. The large jump due to the sensor switch is present in the specific heat measurement but not in the thermal diffusivity measurement.

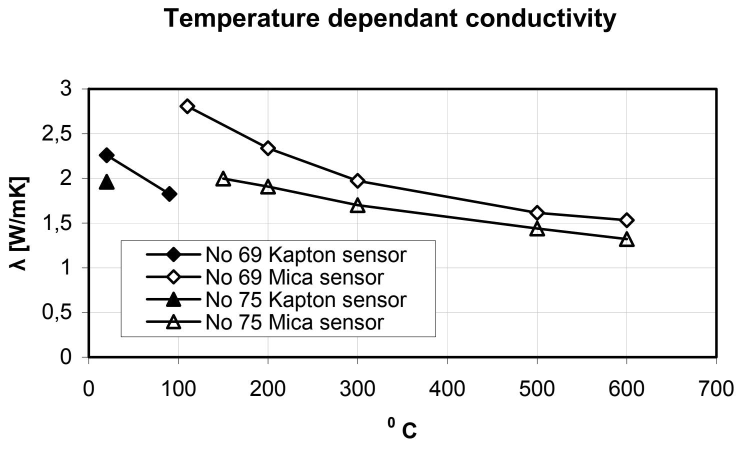


Figure 39. The temperature dependent thermal conductivity for self-compacting concrete. The discrepancy in conductivity for test specimen no 69 is when the sensor was switched from a radius 9.719 mm Kapton to a radius 6.631 mm Mica.

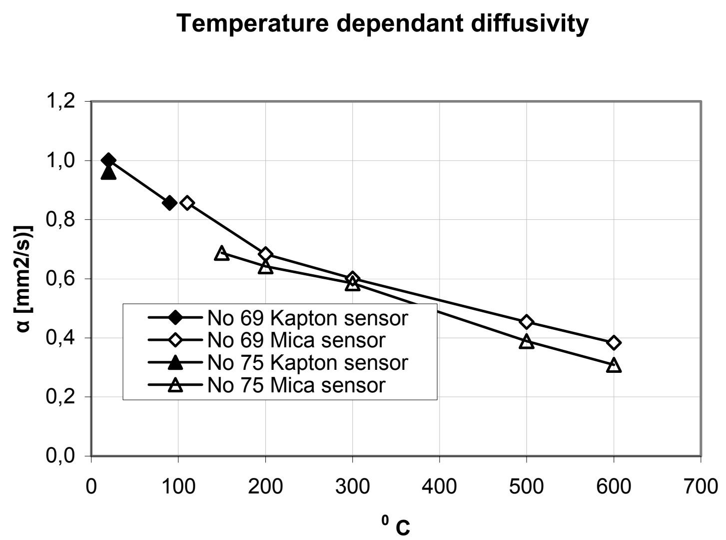


Figure 40. The temperature dependent thermal diffusivity for self-compacting concrete.

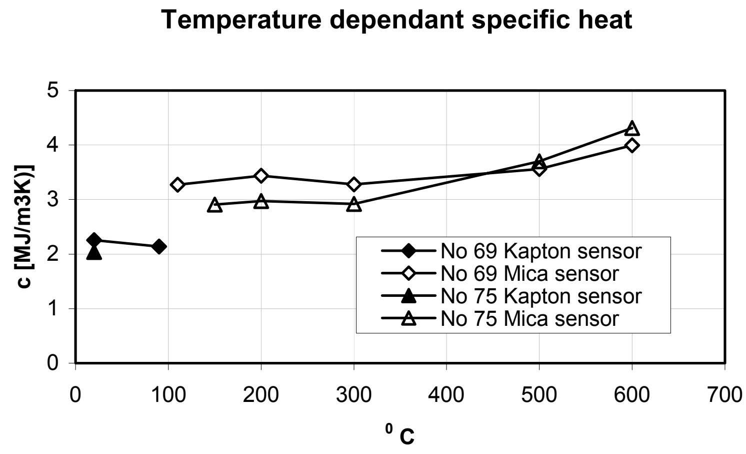


Figure 41. The temperature dependent specific heat for self-compacting concrete. The discrepancy in specific heat for test specimen no 69 is when the sensor was switched from a radius 9.719 mm Kapton to a radius 6.631 mm Mica.

5.3.2 Effect of moisture content

The self-compacting concrete specimens were tested at 75% and 0% RH. The diagram in figure 42 shows a slightly rise in conductivity for the specimens conditioned at 75% RH. No significant moisture dependence of the thermal diffusivity and specific heat is shown in the measurements, figure 43-44.

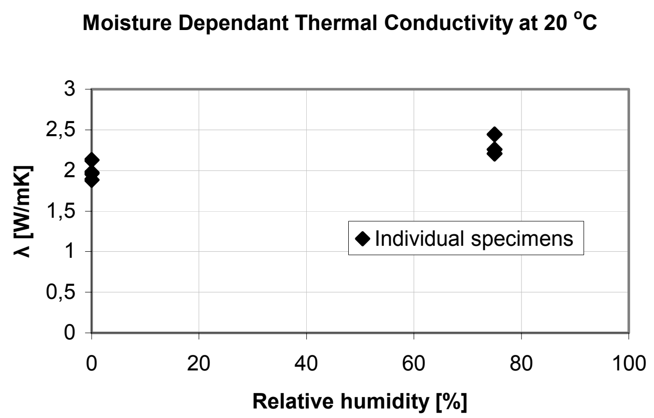


Figure 42. The moisture dependent thermal conductivity for self-compacting concrete at 20 °C.

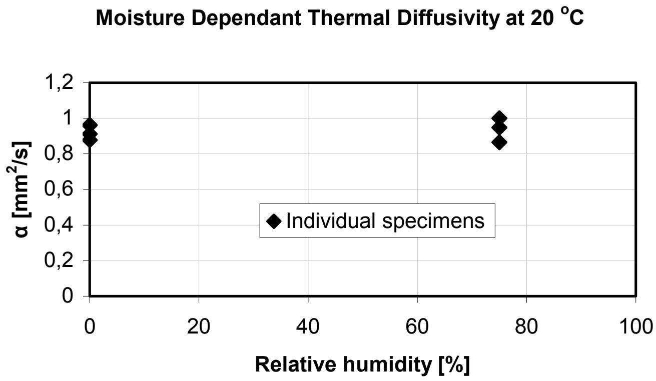


Figure 43. The moisture dependent thermal diffusivity for self-compacting concrete at 20 °C.

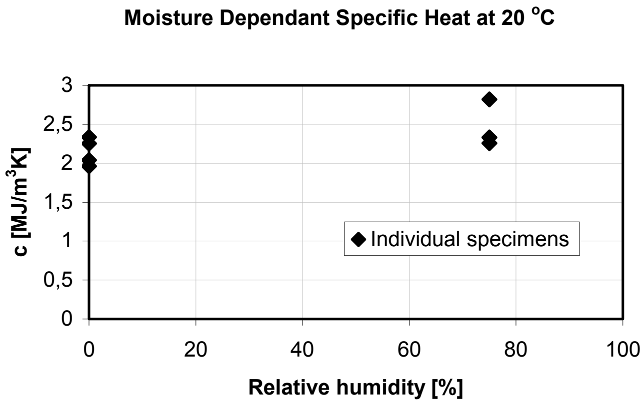


Figure 44. The moisture dependent specific heat for self-compacting concrete at 20 °C.

5.4 Cement paste

Concrete contains of a mix of cement paste and aggregate. The thermal conductivity and thermal diffusivity of cement paste are usually lower than the properties for the aggregate, which leads to lower values of for cement paste compared with concrete.

The measurements on cement paste were done both during the first heating up phase and the cooling down phase, see figures 45-47. The specimens were dried before testing.

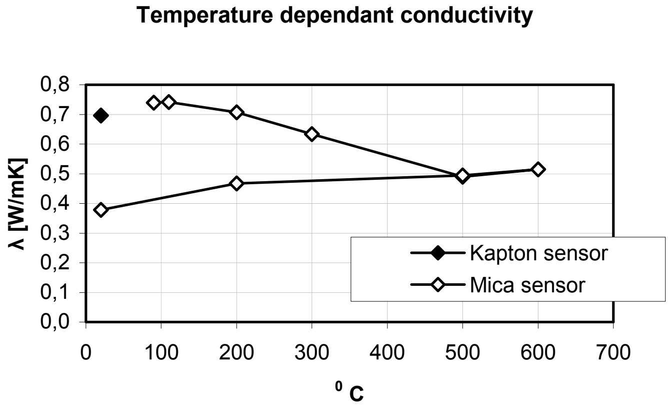


Figure 45. The temperature dependent thermal conductivity for cement paste. The diagram also includes measurements from the cooling down (the lower values). Switched from a radius 9.719 mm Kapton to a radius 6.631 mm Mica at 90 °C.

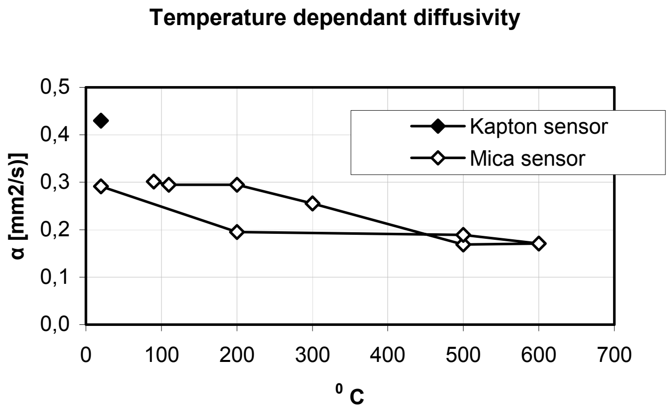


Figure 46. The temperature dependent thermal diffusivity for cement paste. The diagram also includes measurements from the cooling down (the lower values).

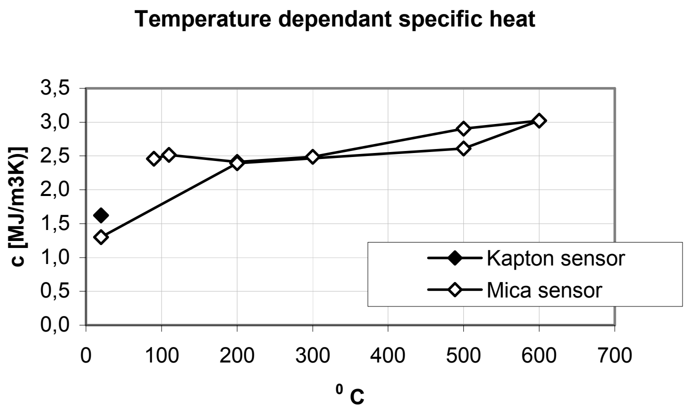


Figure 47. The temperature dependent specific heat for cement paste. The diagram also includes measurements from the cooling down (the lower values).

5.5 Spruce

Wood is a orthotropic material, which means that the thermal properties (conductivity and diffusivity) are different in the three main directions. The main directions in wood are radial, longitudinal and tangential. Therefore test samples with three main directions were prepared to be able to separate the properties. This was shown to be impossible with the available equipment. The development of the TPS system to be able to determine thermal properties in three directions with a special measurement probe and calculation module came to our knowledge during the project but the purchase of this new equipment was not within the scope and time scale of the present project. The difference in the radial and tangential directions are relatively small, about 5-10% according to Kollman and Cote (1968) so as an approximation, wood is treated as an anisotropic material. The thermal properties with two main directions were investigated with the anisotropic module on the specimens with the longitudinal direction placed perpendicular to the TPS sensor.

When measurements on anisotropic materials are performed the specific heat must be known. The specific heat for wood at room temperature was investigated with the special specific heat sensor in the TPS package. The specific heat sensor can only be used at room temperature so specific heat values for higher temperatures were taken from the Eurocode 5: Part 1-2 (2003). The measurements shown in figure 48 and 49 were done on specimens conditioned in 50 % RH.

All individual measurements, which are summarized in the diagrams, are shown in appendix A. As shown in appendix A, when measurements on spruce at temperatures above the room temperature were done, there was a big scatter in the measured values. This fact is not satisfactory and must be dealt with to get reliable values in future measurements.

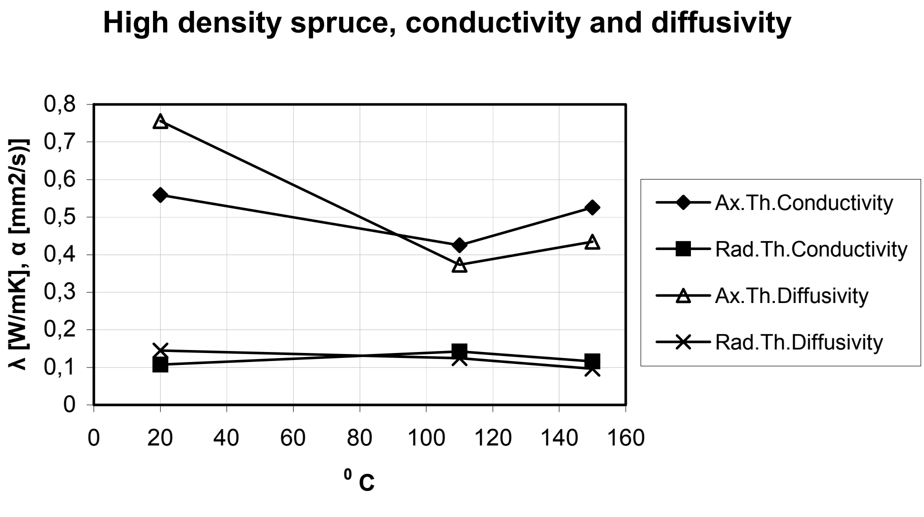


Figure 48. The temperature dependent axial and radial thermal conductivity and diffusivity for high-density spruce. Axial in the measurements is longitudinal in the material and radial is radial and tangential in the living tree.

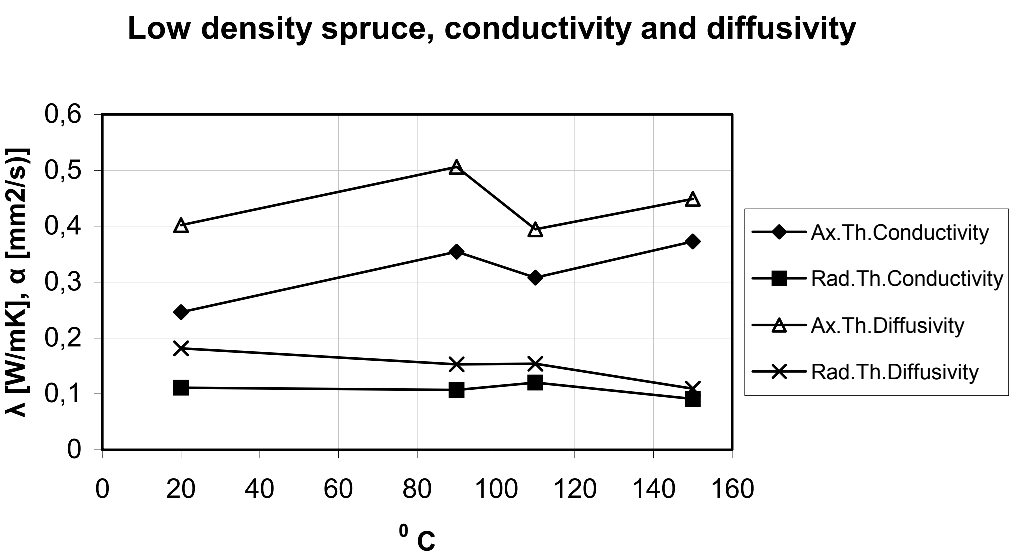


Figure 49. The temperature dependent axial and radial thermal conductivity and diffusivity for low-density spruce. Axial in the measurements is longitudinal in the material and radial is radial and tangential in the living tree.

5.6 Particleboard

Density of the material was 595 kg/m^3 and the initial moisture content u=7 %.

The thermal conductivity for particleboard is according to Kollman and Cote (1968) just between fiber-based board and wood in transverse direction in figure 8 in the literature survey chapter, i.e. approximately 0.1 W/mK which should bee compared with 0.18 for particleboard, see figure 50, from the TPS measurements, which is a big difference. The discrepancy may possibly depend on development of the materials, the diagrams in the publication by Kollman and Cote is based on measurements from 1956. As indicated in table 14 the thermal conductivity is slightly rising with increasing moisture content, which is logical. The conductivity measurements of particleboard shown in the NIST database (ID 1897) seem to be more in the same range as the TPS measurements. They measured 0.15 W/mK for a particleboard with the density 795 kg/m^3 which should bee compared with 0.18/0.16 W/mK for dry/wet 595 kg/m^3 material with the TPS method.

The values at 192 °C in figures 50-52 are uncertain since pyrolysis occurred in the samples.

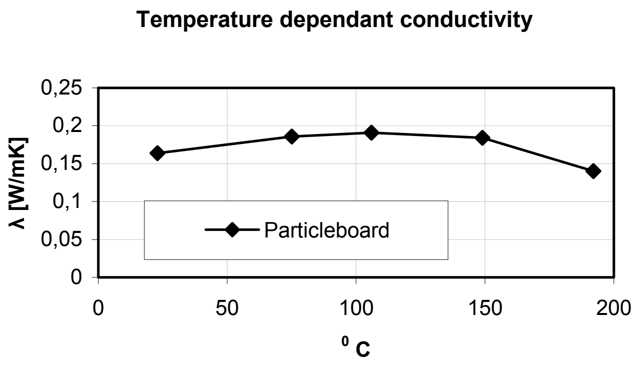


Figure 50. The temperature dependent thermal conductivity for particleboard.

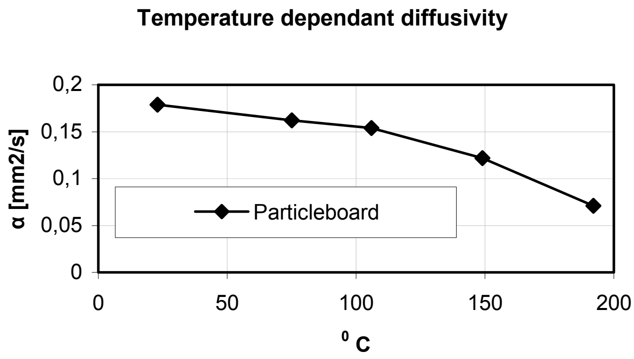


Figure 51. The temperature dependent thermal diffusivity for particleboard.

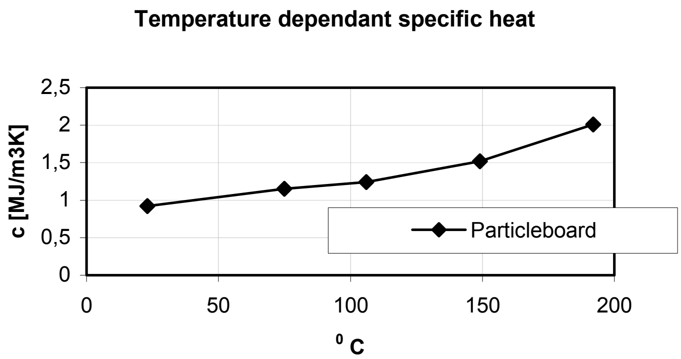


Figure 52. The temperature dependent specific heat for particleboard.

Table 14. At 20 °C

Moisture content	Conductivity (W/mK)	Diffusivity (mm^2/s)	Specific heat (MJ/m^3K)	Number of specimens
0	0.164	0.179	0.92	6
7	0.176	0.172	1.027	4

5.7 Fibreboard

Density of the material was 278 kg/m^3 and the initial moisture content u=7 %.

The conductivity values from the measurements on fibreboard do not correspond well with the values reported by Kollman and Cote (1968). As seen in the literature survey chapter, figure 8, they report approximately 0.05 W/mK for fibre-based board at room temperature with 12 % moisture in the material that should be compared with 0.10 for fibreboard with 7 % moisture content. As indicated in table 15 the thermal conductivity is rising with increasing moisture content, which is logical. The discrepancy may possibly depend on development of the materials, the diagrams in the publication by Kollman and Cote is based on measurements from 1956.

Table 15. At 23 °C

Moisture content	Conductivity (W/mK)	Diffusivity (mm^2/s)	Specific heat (MJ/m^{3}K)	Number of specimens
0	0.088	0.323	0.273	4
7	0.101	0.294	0.343	6

The temperature dependant thermal conductivity, thermal diffusivity an specific heat are shown in figures 53-55 respectively.

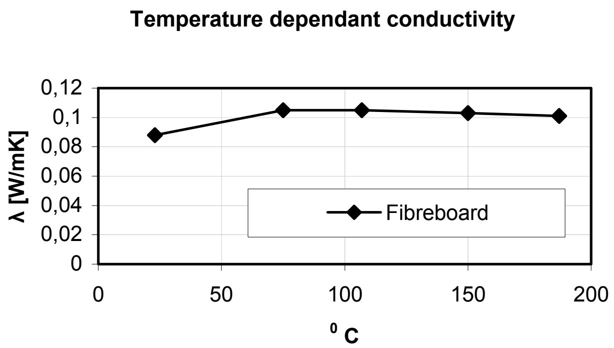


Figure 53. The temperature dependent thermal conductivity for fibreboard.

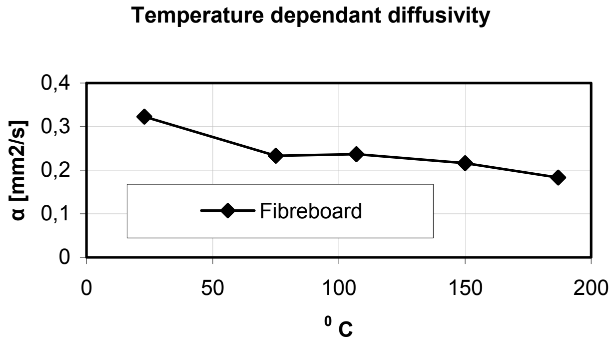


Figure 54. The temperature dependent thermal diffusivity for fibreboard.

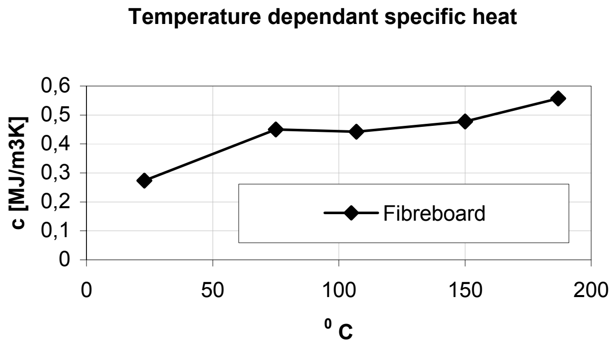


Figure 55. The temperature dependent specific heat for fibreboard.

5.8 Polymethylmetacrylate (PMMA)

Density of the material was 1176 kg/m^3. The thermal properties, figures 56-58, of PMMA seems to be quite stable in the tested temperature interval.

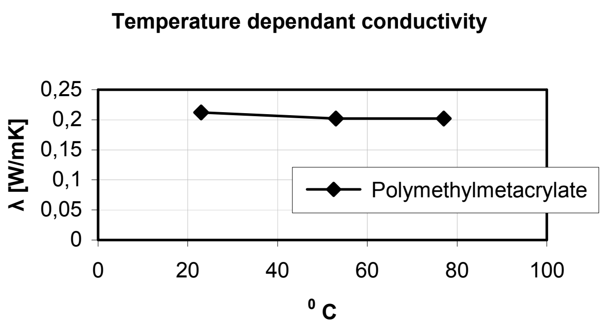


Figure 56. The temperature dependent thermal conductivity for polymethylmetacrylate.

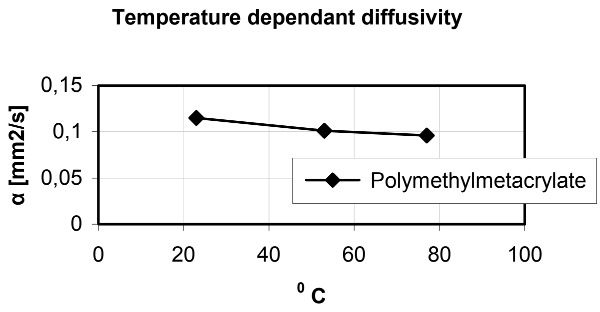


Figure 57. The temperature dependent thermal diffusivity for polymethylmetacrylate.

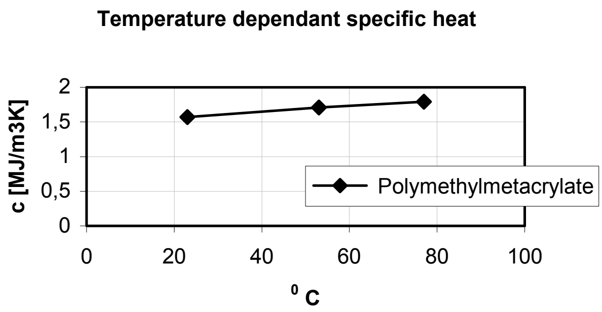


Figure 58. The temperature dependent specific heat for polymethylmetacrylate.

5.9 Insulation and plastic materials

5.9.1 Polystyrene

The thermal conductivity, specific heat and diffusivity is rising with the temperature, see table 16.

Table 16.

Temperature	Conductivity (W/mK)	Diffusivity (mm^2/s)	Specific heat (MJ/m^3K)
20 °C	0.038	1.42	0.027
85 °C	0.048	1.53	0.032

5.9.2 Flexible Polyurethane foam

At temperatures near 100 °C the material was "melting" i.e. the material was shrinking rapidly on the surface near the sensor when the temperature was raised 3-5 degrees during measurements. That was the reason for the choice of 85 °C as the highest temperature. As seen in table 17 there is some effect of the temperature on the thermal properties. The thermal conductivity and the thermal diffusivity become higher and the specific heat is lower when the temperature is increased.

Table 17. 50% RF

Temperature	Conductivity (W/mK)	Diffusivity (mm^2/s)	Specific heat (MJ/m^3K)
20 °C	0.043	0.46	0.096
85 °C	0.051	1.18	0.043

5.9.3 High-density glass wool

The high-density glass wool tested in this investigation is treated as an isotropic material i.e. no direction dependence in the thermal properties are supposed to exist. This is an assumption because the samples are more or less orthotropic due to the orientation of the fibres in the material. This orthotropic behaviour directly leads to an error in the measurement with the standard module. If the material is anisotropic i.e. the different directions in the material are in the plane and perpendicular to the plane the anisotropy module in the TPS package can be used, but then the temperature dependent volumetric specific heat must be used as input. To determine the temperature dependent volumetric specific heat by some other method is outside the scope of this project so the standard module associated with the above-mentioned problem was used.

The results from the measurements o high-density glass wool are shown in figures 59-61. The thermal conductivity and thermal diffusivity rises with temperature and the temperature dependence of the specific heat is more like a parabola function.

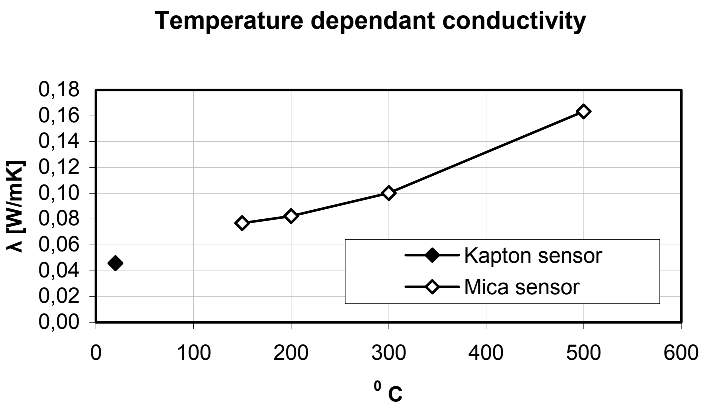


Figure 59. The temperature dependent thermal conductivity for high-density glass wool.

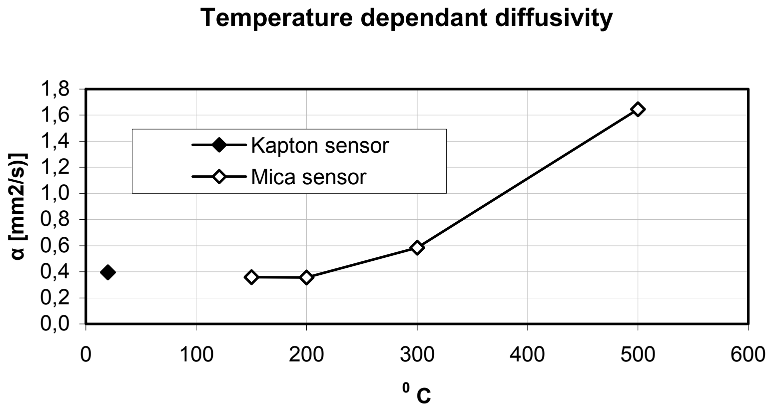


Figure 60. The temperature dependent thermal diffusivity for glass wool.

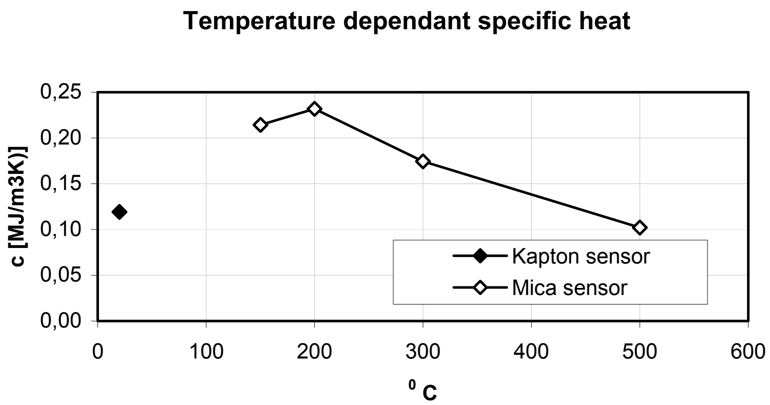


Figure 61. The temperature dependent specific heat for glass wool.

5.9.4 Low-density glass wool

During testing there was evident that the switch from Kapton insulated sensors to Mica insulated ones for high temperatures showed a very unphysical discrepancy in the measured values especially for the low density materials, low density glass wool (29 kg/m^3) and mineral wool (33 kg/m^3). This is a fundamental problem, which must be solved if reliable measurements are going to be performed at high temperatures. The temperature dependant thermal properties are shown in figures 62-64.

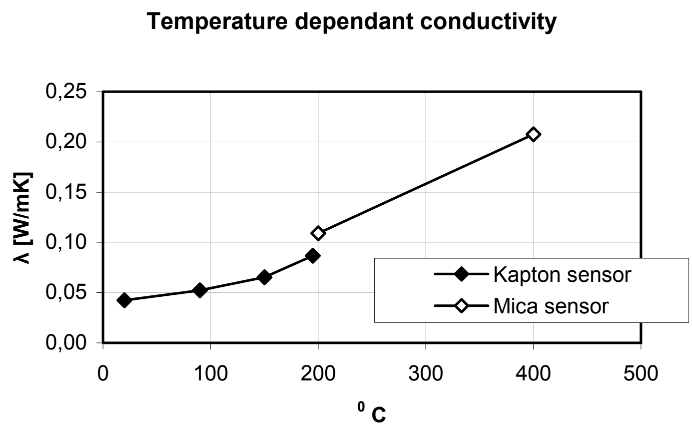


Figure 62. The temperature dependent thermal conductivity for low-density glass wool. There is an unphysical jump between the different sensors, see previous chapter.

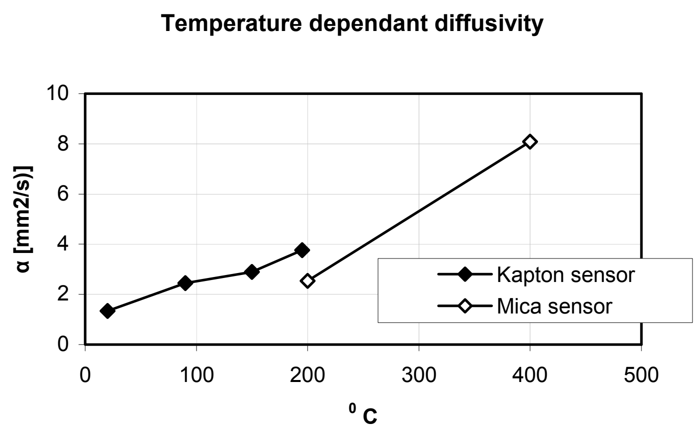


Figure 63. The temperature dependent thermal diffusivity for low-density glass wool. There is an unphysical jump between the different sensors, see previous chapter.

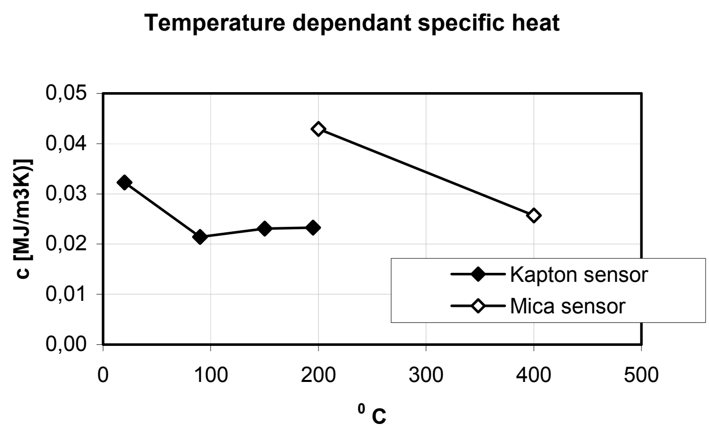


Figure 64. The temperature dependent specific heat for low-density glass wool. There is an unphysical jump between the different sensors, see previous chapter.

5.9.5 Mineral Wool

As in the measurements on low-density glass wool an unphysical step is present when the sensor is switched from Kapton to Mica. This reason for this must be further investigated to be able to determine the thermal properties of this type of material. Figures 65-68 shows the thermal conductivity, thermal diffusivity and the specific heat respectively.

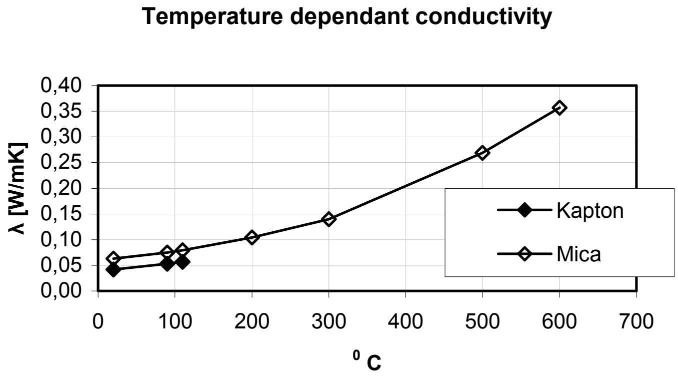


Figure 65. The temperature dependent thermal conductivity for low-density mineral wool. There is an unphysical jump between the different sensors, see discussion in the beginning of this chapter.

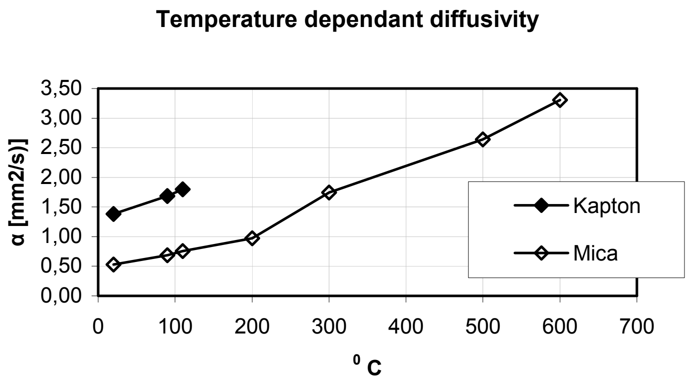


Figure 66. The temperature dependent thermal diffusivity for low-density mineral wool. There is an unphysical jump between the different sensors, see discussion in the beginning of this chapter.

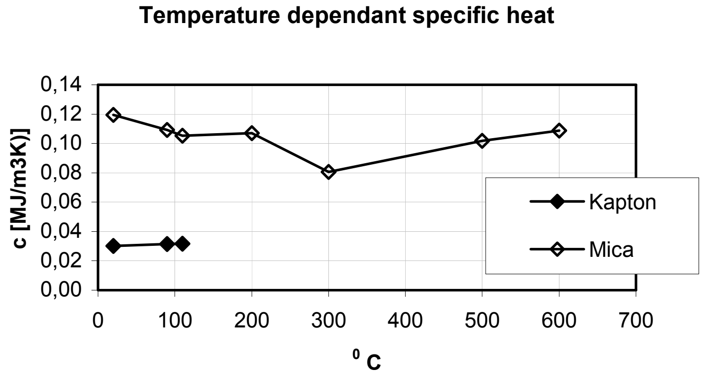


Figure 67. The temperature dependent specific heat for low-density mineral wool. There is an unphysical jump between the different sensors, see discussion in the beginning of this chapter.

6 Full scale test and calculation

6.1 Experimental measurements

A full-scale test (Boström 2004) was carried out with a self-compacting concrete containing polypropylene fibres. The test was a part of a research project aimed to develop a suitable test methodology for determination of fire spalling.

The concrete recipe is shown in table 18. A slab with the dimensions 1800 x 1200 x 200 mm^3 was manufactured. In addition to the full scale specimen cubes with the dimensions 150 x 150 x 150 mm^3 were manufactured for measurement of the thermal properties by TPS see chapter 6.2.

Table 18. Concrete mixture (Boström 2004).

Dry materials (kg/m^3)		
Cement	Slite (CEM I)	380.76
Limestone filler	Limus 25	119.24
Fine gravel	0-8 Sätertorp	899.96
Coarse gravel	8-16 Sätertorp	721.90
Plasticizer*	CemFlux Prefab	5.73
Plasticizer	(% of C+F)	1.15%
Fibres	Fibrin 18µm	1.0
Water/moisture (kg/m^3)		
Water		149.69
Dilution water		10.02
Moisture in material		37.54
w/c-ratio		0.518

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

The cube strength of the concrete was measured after 7 days, 28 days and at the time of the fire test, i.e. at an age of 3 months. In table 19 are the strength values given.

Table 19. Concrete strength w/p=0.40 with fibres (Boström 2004).

	7 days	28 days	Day of fire test
Mean (MPa)	38.1	53.6	58.6

The moisture content of the specimens was measured on the same cubes as used for measurement of compressive strength after 3 months. The cubes were weighted after the compressive tests and then placed in an oven. They were dried in 105 °C for 30 days and thereafter weighted again. The determined moisture content was 4.8 %.

The fire test was performed according to the fire curve described in EN 1363-1 and the tested slab was loaded in compression with 30% of f_u. EN 1363-1 is the new European varian of the standard tile temperature curve and f_u is the compressible strength at room temperature. Temperature measurements with thermocouples, which were attached to the specimen during the casting, were performed on 5 different depths, see figure 68.

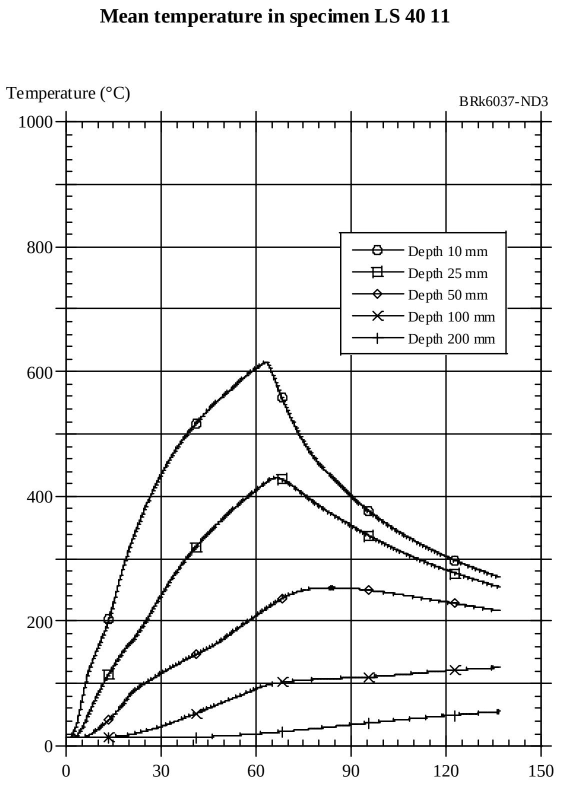


Figure 68. Measured temperatures at different depths of the test specimen (Boström 2004).

6.2 TPS measurements

Temperature calculations based on measured thermal properties were performed to investigate the possibility to predict the temperature increase in a fire exposed concrete slab.

Measurements of the thermal properties were performed on concrete from the full-scale test described in chapter 6.1. The cubes with the dimensions 150 x 150 x 150 mm^3 were sliced in pieces with the dimensions 70 x 70 x 25 mm^3 suitable for TPS measurements. The temperature sequence for the test on concrete was chosen to be 20, 90, 110, 200, 500, 600, 500, 200 and 20 °C. The decrease of the temperature from 600 to 20 °C was performed to see if the thermal conductivity was to remain constant during cooling as reported in the literature, see chapter 1.2.1. At every temperature level the measurement was performed when the test sample had a uniform temperature distribution. In figure 69, the thermal conductivity from the measurements is presented and in figure 70 the thermal diffusivity is shown. As explained earlier the thermal conductivity, thermal diffusivity and the specific heat are determined simultaneously i.e. in the same measurement. The TPS measurements were preformed on dried material.

Two complementary tests of the specific heat were done with a MDSC (Modulated Differential Scanning Calorimeter) to ensure that the TPS sensor had “seen” a representative mix of the material. This extra comparison may not have been necessary if a bigger sensor had been used, see discussion in chapter 6.1.

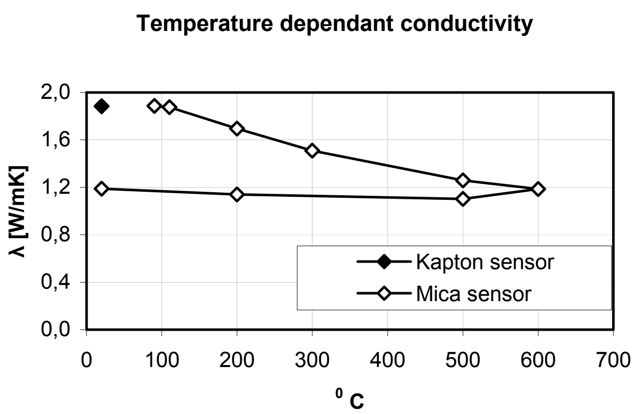


Figure 69. The thermal conductivity for the tested concrete at different temperatures and place in the heating cycle. The heating cycle starts at the highest conductivity value at 20 °C.

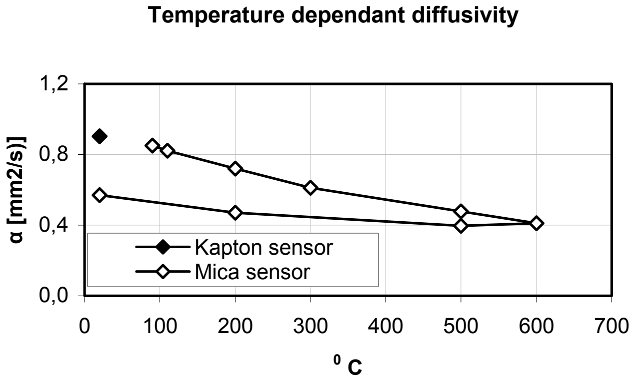


Figure 70. The thermal diffusivity for the tested concrete at different temperatures and place in the heating cycle. The heating cycle starts at the highest diffusivity value at 20 °C.

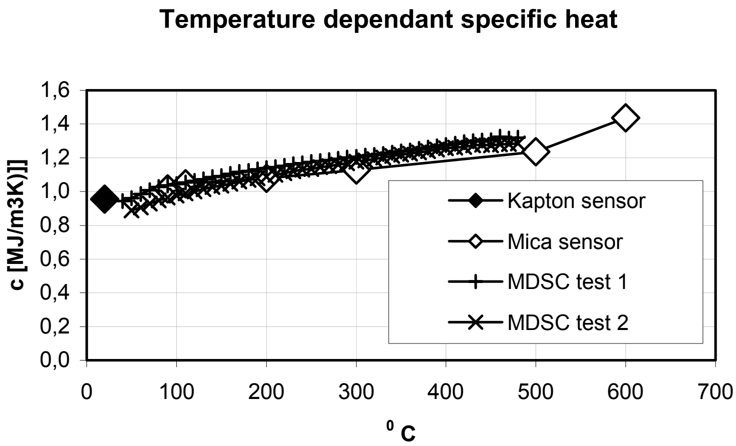


Figure 71. Specific heat measured with the TPS method and a Modulated Differential Scanning Calorimeter.

6.3 Calculation and comparison between experimental and theoretical results

The calculation was performed with the finite difference code TASEF (Wickström 1989) based on thermal properties from TPS measurements and the boundary conditions from the real fire test described in chapter 6.1. The chosen boundary condition was the measured temperature 10 millimetres from the fire-exposed side of the slab and the comparison between calculated and measured temperatures was done on 25 and 50 millimetres from the fire exposed side. The reason for using the temperature measured at 10 mm as input and not the furnace temperature was to eliminate the uncertainty at the radiation/convection boundary and the fact that the thermal properties were only investigated up to 600 °C.

Additional input in the calculation was the influence of moisture in the material. The TPS measurements were preformed on dried material and the latent heat is not possible to determine with the TPS method. The latent heat of water is accounted for in the 100-150 degrees region as well as the energy needed for heating up the water to 100 degrees (about 10% of the latent heat energy).

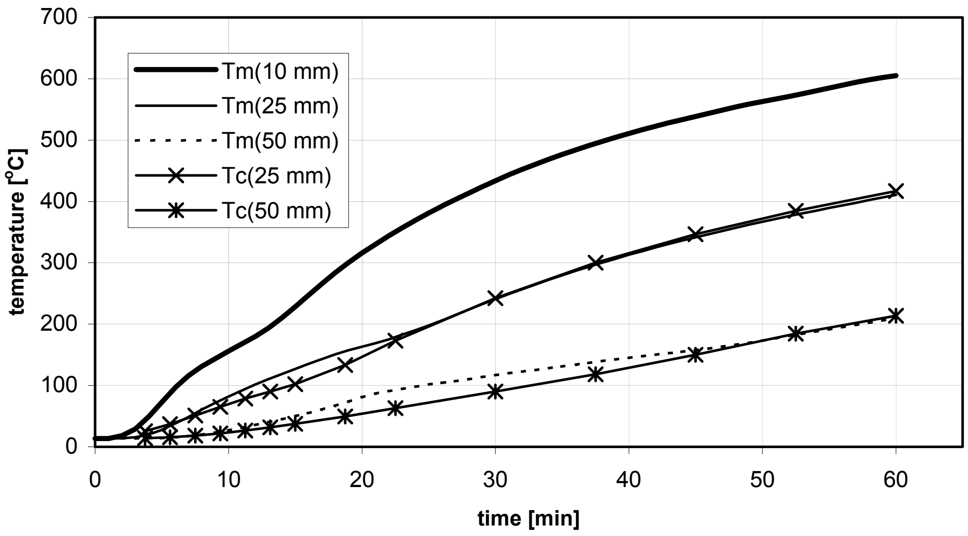


Figure 72. Temperature curves from the measurement, Tm = temperature measurement, Tc = temperature calculation.

The calculated temperature response, Tc, shown in figure 72 shows a good agreement with temperature measurements Tm. The only significant difference is in the 100 °C region which is probably caused by moisture movements or/and pressure dependent boiling points, which are not taken into account in the model.

The numerical simulation on the temperature rise of a fire-tested concrete slab based on measured thermal properties shows a good correspondence with the real fire test. Also the comparison between the specific heat measurements with TPS and MDSC looks promising.

Discussion

This chapter deals only with an additional discussion about concrete and wood materials. Other discussions are present in chapter 5, “Test procedure and results”.

6.4 Concrete materials

The measurements on concrete at high temperatures were done with Mica sensors with diameters 6.631 and 9.719 mm. As discussed in chapter 5.1 the small size of the sensors introduced a scatter in the results by the difference in thermal properties between the aggregate and the cement paste in concrete. The sensor will determine a more representative mix of the components if the diameter of the sensor is larger. A sensor radius of approximately 24 mm is recommended for future measurements. As a consequence the size of the test specimens also ought to be increased to approximately a thickness of 48 mm and radius of 100 mm.

As seen in chapter 1.2.1 the reported values of the thermal properties for different concretes may vary relatively much. In the Eurocode 2 part 1-2 (2003) this is dealt with by giving an upper and a lower curve of the temperature dependent conductivity. The trend from the measurements performed in this project is that the conductivity for the tested concretes is slightly higher than the stated values in the upper curve in the Eurocode. On the other hand the specific heat also seems to be slightly higher then the Eurocode so the ratio between the properties, the diffusivity, does not diverge. The diffusivity of conventional concrete is slightly lower than for high performance and self-compacting concrete.

The results of the numerical calculation based on measured properties shows a good agreement with measured temperature values from a real fire test. This is a promising result.

6.5 Wood and wood based products

The first intension with the tests on spruce was to be able to determine the thermal properties in three different directions. This was shown to be impossible with the standard equipment. A special sensor and calculation module must be used but that was outside the scope of this project. But with the anisotropy module of the TPS package at least the properties in two directions could be determined. This is possible if the volumetric specific heat is known in advance. The volumetric specific heat at room temperature was determined with the special designed specific heat sensor in the TPS package and at higher temperatures the value was taken from the Eurocode, which introduce an unknown amount of uncertainty. Another problem is that when using the anisotropy module it is assumed that the thermal properties are constant in the plane and perpendicular to the plane. This is not exactly truth for wood so the measurements done in this project on spruce shall be seen as indicative results. Although the measured values on the radial thermal conductivity do in fact correspond well with the values from the Eurocode, which is shown when comparing the measured values in figures 48-49 with the values from the Eurocode in figure 9.

7 Conclusions

Measurements of the thermal properties with the TPS (Transient Plane Source) method have been performed on different kind of building materials. The measurements were performed at different temperatures and moisture conditions. The following conclusions for different materials were drawn from the tests.

Concrete:

- A proper diameter of the sensor is important. Three times the size of the biggest aggregate in the concrete is a role of thumb.
- Good agreement between measurements of the specific heat with TPS and MDSC (Modulated Differential Scanning Calorimeter) were observerd.
- There is already a good agreement between temperature simulation based on TPS data and a real fire test, despite of the fact that some physical phenomena are not included in the model.
- The thermal conductivity and specific heat for high performance and self-compacting concrete is slightly higher than the values in the Eurocode 2 part 1-2 (2003) but the diffusivity is approximately the same. The values for conductivity are near the upper curve in the Eurocode. The diffusivity for conventional concrete is slightly lower than for high performance and self-compacting concrete.
- Because of the small change of thermal conductivity during cooling the residual value of the thermal conductivity might be a way of looking at the value at high temperature. But it ought to be further investigated.

Wood and wood based products:

- Measurement on wood corresponded well with the Eurocode in the radial direction.
- Repeated measurements on the same temperature level showed big scatter. The reason for this must be further investigated.
- The measurements at room temperature on particleboard corresponded fairly well with the values from measurements performed at NIST (ID 1897).
- Measurements of the thermal conductivity and diffusivity in three directions for wood were not included in this project but need to be investigated further.

Insulating and plastic materials:

- Temperature dependent volumetric specific heat needs to be known if the materials are anisotropic

- There are still problems with big differences in measured values between Kapton insulated sensors and Mica insulated sensors when measurements are performed on low-density materials like mineral wool and glass wool.
- If the material has more than two main directions on the thermal properties the measurement must be performed with specially designed equipment, which was outside of the scope of this project.

The present study shows some pros and cons with the TPS technique. Because of the shape of the sensor and the fact that the temperature field not is one-dimensional it is possible to determine the thermal conductivity, diffusivity and volumetric specific heat simultaneously for isotropic materials. But with anisotropic material the same fact, that the temperature field is not one dimensional, requires knowledge the volumetric specific heat in advance to be able to perform any kind of measurement.

8 Purposed areas for further investigation

The TPS approach to measure the thermal properties is very interesting but in some areas the method ought to be investigated further:

- The use of the residual value for concrete after drying at high temperature for assessment of the thermal conductivity at high temperature. The goal of this work should be to verify if the thermal conductivity always is stable during cooling.
- The possibility of measurement of the thermal properties in three directions in wood and fibre insulation with the transient hot strip.
- The reason for the big scatter in the wood measurements. Is it due to internal reactions?
- The reason for the big difference between Kapton and Mica sensors when measurements are performed on low-density mineral- and glass wool.

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Appendix A – Data from measurements

Conventional concrete

No 38 RH 0%

	Th.Conductivity	**Th.Diffusivity**	**Spec.Heat**
	20^{o}C, Kapton 9,719 mm		
Measure 1	1,53	0,85	1,80
Measure 2	1,54	0,84	1,82
Measure 3	1,54	0,84	1,84
Measure 4	1,54	0,86	1,80
Measure 5	1,55	0,87	1,78
Mean value	**1,54**	**0,85**	**1,81**
C.O.V (%)	**0,5**	**1,5**	**1,2**
	90^{o}C, Mica 9,719 mm		
Measure 1	1,62	0,70	2,29
Measure 2	1,61	0,73	2,20
Measure 3	1,61	0,73	2,20
Measure 4	1,61	0,69	2,35
Measure 5	1,62	0,71	2,27
Mean value	**1,61**	**0,71**	**2,26**
C.O.V (%)	**0,3**	**2,8**	**2,9**
	110^{o}C, Mica 9,719 mm		
Measure 1	1,59	0,66	2,40
Measure 2	1,60	0,69	2,30
Measure 3	1,60	0,67	2,37
Measure 4	1,60	0,68	2,36
Measure 5	1,59	0,71	2,24
Mean value	**1,59**	**0,68**	**2,34**
C.O.V (%)	**0,4**	**2,6**	**2,7**
	200^{o}C, Mica 9,719 mm		
Measure 1	1,43	0,52	2,74
Measure 2	1,44	0,55	2,63
Measure 3	1,45	0,56	2,61
Measure 4	1,47	0,58	2,55
Measure 5	1,46	0,57	2,57
Measure 6	1,46	0,58	2,53
Measure 7	1,46	0,59	2,47
Mean value	**1,45**	**0,56**	**2,59**
C.O.V (%)	**0,8**	**3,9**	**3,3**

	400°C, Mica 9,719 mm		
Measure 1	1,51	0,44	3,39
Measure 2	1,61	0,57	2,83
Measure 3	1,54	0,53	2,90
Measure 4	1,45	0,46	3,11
Measure 5	1,37	0,40	3,44
Measure 6	1,39	0,39	3,52
Measure 7	1,42	0,40	3,53
Measure 8	1,42	0,42	3,40
Measure 9	1,36	0,34	4,03
Measure 10	1,41	0,40	3,52
Measure 11	1,50	0,50	3,02
Measure 12	1,48	0,48	3,06
Measure 13	1,67	0,69	2,43
Measure 14	1,38	0,38	3,62
Measure 15	1,39	0,36	3,88
Measure 16	1,42	0,40	3,58
Mean value	**1,46**	**0,45**	**3,33**
C.O.V (%)	**6,1**	**20,0**	**12,4**
	600°C, Mica 9,719 mm		
Measure 1	1,13	0,31	3,61
Measure 2	1,17	0,39	3,03
Measure 3	1,15	0,35	3,26
Measure 4	1,03	0,25	4,12
Measure 5	1,06	0,25	4,28
Measure 6	1,10	0,33	3,37
Measure 7	1,01	0,24	4,22
Measure 8	1,01	0,21	4,75
Measure 9	1,03	0,23	4,56
Measure 10	1,14	0,32	3,54
Measure 11	1,10	0,28	4,00
Measure 12	1,09	0,29	3,80
Measure 13	1,14	0,29	3,89
Measure 14	1,13	0,33	3,40
Measure 15	1,13	0,32	3,58
Mean value	**1,09**	**0,29**	**3,83**
C.O.V (%)	**4,9**	**17,1**	**12,9**

No 23 RH 33%

	Th.Conductivity	**Th.Diffusivity**	**Spec.Heat**
	110^{o}C, Mica 9,719 mm		
Measure 1	2,45	0,82	2,98
Measure 2	2,41	0,79	3,06
Measure 3	2,42	0,81	2,98
Measure 4	2,44	0,84	2,92
Measure 5	2,43	0,82	2,97
Mean value	**2,43**	**0,81**	**2,98**
C.O.V (%)	**0,7**	**2,2**	**1,7**
	200^{o}C, Mica 9,719 mm		
Measure 1	1,98	0,72	2,76
Measure 2	1,96	0,64	3,04
Measure 3	1,96	0,66	2,98
Mean value	**1,97**	**0,67**	**2,93**
C.O.V (%)	**0,6**	**6,0**	**5,2**
	300^{o}C, Mica 9,719 mm		
Measure 1	1,65	0,56	2,96
Measure 2	1,66	0,59	2,82
Measure 3	1,61	0,52	3,09
Measure 4	1,62	0,54	2,97
Measure 5	1,51	0,41	3,65
Mean value	**1,61**	**0,53**	**3,10**
C.O.V (%)	**3,6**	**12,7**	**10,4**
	500^{o}C, Mica 9,719 mm		
Measure 1	1,36	0,42	3,26
Measure 2	1,40	0,45	3,12
Measure 3	1,36	0,42	3,26
Measure 4	1,33	0,40	3,34
Measure 5	1,33	0,40	3,34
Measure 6	1,32	0,40	3,26
Measure 7	1,35	0,44	3,08
Measure 8	1,31	0,38	3,43
Mean value	**1,35**	**0,41**	**3,26**
C.O.V (%)	**2,2**	**5,4**	**3,6**
	600^{o}C, Mica 9,719 mm		
Measure 1	1,24	0,33	3,79
Measure 2	1,25	0,33	3,84
Measure 3	1,19	0,28	4,23
Measure 4	1,21	0,32	3,83
Mean value	**1,22**	**0,31**	**3,92**
C.O.V (%)	**2,4**	**7,0**	**5,3**

No 1, RH 97%	Th.Conductivity	Th.Diffusivity	Spec.Heat
	20^{o}C, Kapton 9,719 mm		
Measure 1	2,34	0,98	2,40
Measure 2	2,33	0,97	2,41
Measure 3	2,34	0,98	2,39
Mean value	**2,34**	**0,97**	**2,40**
C.O.V (%)	**0,2**	**0,5**	**0,3**

No 2, RH 97%			
	20^{o}C, Kapton 9,719 mm		
Measure 1	2,24	1,09	2,06
Measure 2	2,22	1,06	2,09
Measure 3	2,23	1,08	2,07
Measure 4	2,23	1,05	2,12
Mean value	**2,23**	**1,07**	**2,08**
C.O.V (%)	**0,4**	**1,4**	**1,2**

No 3, RH 97%			
	20^{o}C, Kapton 9,719 mm		
Measure 1	2,37	0,82	2,88
Measure 2	2,36	0,81	2,93
Measure 3	2,36	0,81	2,91
Measure 4	2,37	0,81	2,91
Mean value	**2,36**	**0,81**	**2,91**
C.O.V (%)	**0,2**	**0,9**	**0,7**

No 17, RH 75%			
	20^{o}C, Kapton 9,719 mm		
Measure 1	1,89	0,87	2,18
Measure 2	1,90	0,88	2,18
Measure 3	1,90	0,84	2,27
Measure 4	1,90	0,87	2,18
Mean value	**1,90**	**0,86**	**2,20**
C.O.V (%)	**0,2**	**2,1**	**2,1**

No 18, RH 75%			
	20^{o}C, Kapton 9,719 mm		
Measure 1	1,97	0,94	2,08
Measure 2	1,97	0,95	2,07
Measure 3	1,98	0,98	2,03
Mean value	**1,97**	**0,96**	**2,06**
C.O.V (%)	**0,4**	**1,9**	**1,5**

No 19, RH 75%			
	20^{o}C, Kapton 9,719 mm		
Measure 1	2,05	0,87	2,36
Measure 2	2,06	0,88	2,35
Measure 3	2,07	0,90	2,30
Measure 4	2,07	0,89	2,33
Measure 5	2,07	0,88	2,35
Mean value	**2,06**	**0,88**	**2,34**
C.O.V (%)	**0,5**	**1,4**	**1,0**

No 21, RH 33%

	20°C, Kapton 9,719 mm		
Measure 1	1,81	0,99	1,82
Measure 2	1,81	1,02	1,78
Measure 3	1,82	1,04	1,75
Measure 4	1,81	1,02	1,78
Mean value	**1,81**	**1,02**	**1,78**
C.O.V (%)	**0,3**	**2,0**	**1,8**

No 26, RH 33%

	20°C, Kapton 9,719 mm		
Measure 1	2,01	1,21	1,65
Measure 2	2,01	1,23	1,63
Measure 3	2,00	1,20	1,67
Mean value	**2,00**	**1,21**	**1,65**
C.O.V (%)	**0,4**	**1,3**	**1,0**

No 27, RH 33%

	20°C, Kapton 9,719 mm		
Measure 1	1,81	1,03	1,75
Measure 2	1,84	1,06	1,75
Measure 3	1,85	1,10	1,68
Measure 4	1,86	1,11	1,67
Measure 5	1,85	1,06	1,74
Measure 6	1,87	1,13	1,66
Mean value	**1,84**	**1,08**	**1,71**
C.O.V (%)	**1,1**	**3,4**	**2,5**

No 32, RH 50%

	20°C, Kapton 9,719 mm		
Measure 1	1,81	1,10	1,64
Measure 2	1,80	1,09	1,65
Measure 3	1,80	1,09	1,65
Measure 4	1,80	1,08	1,66
Mean value	**1,80**	**1,09**	**1,65**
C.O.V (%)	**0,4**	**0,8**	**0,4**

No 33, RH 50%

	20°C, Kapton 9,719 mm		
Measure 1	1,92	0,94	2,05
Measure 2	1,91	0,92	2,08
Measure 3	1,92	0,93	2,06
Measure 4	1,91	0,92	2,08
Mean value	**1,92**	**0,93**	**2,07**
C.O.V (%)	**0,4**	**1,2**	**0,8**

No 34, RH 50%

	20°C, Kapton 9,719 mm		
Measure 1	2,22	1,03	2,16
Measure 2	2,21	1,01	2,19
Measure 3	2,22	1,03	2,15
Measure 4	2,21	1,01	2,19
Measure 5	2,21	1,01	2,18
Mean value	**2,21**	**1,02**	**2,18**
C.O.V (%)	**0,3**	**1,0**	**0,8**

No 35, RH 50%

	20°C, Kapton 9,719 mm		
Measure 1	1,80	0,91	1,97
Measure 2	1,79	0,90	1,99
Measure 3	1,78	0,90	1,98
Measure 4	1,78	0,90	1,97
Mean value	**1,79**	**0,90**	**1,98**
C.O.V (%)	**0,4**	**0,8**	**0,5**

No 36, RH 0%

	20°C, Kapton 9,719 mm		
Measure 1	1,73	0,97	1,78
Measure 2	1,75	1,01	1,73
Measure 3	1,75	1,03	1,70
Measure 4	1,75	1,05	1,67
Mean value	**1,75**	**1,02**	**1,72**
C.O.V (%)	**0,6**	**3,4**	**2,9**

No 37, RH 0%

	20°C, Kapton 9,719 mm		
Measure 1	1,55	0,90	1,73
Measure 2	1,55	0,91	1,70
Measure 3	1,55	0,90	1,72
Mean value	**1,55**	**0,90**	**1,72**
C.O.V (%)	**0,2**	**0,5**	**0,7**

No 38, RH 0%

	20°C, Kapton 9,719 mm		
Measure 1	1,53	0,85	1,80
Measure 2	1,54	0,84	1,82
Measure 3	1,54	0,84	1,84
Measure 4	1,54	0,86	1,80
Measure 5	1,55	0,87	1,78
Mean value	**1,54**	**0,85**	**1,81**
C.O.V (%)	**0,5**	**1,5**	**1,2**

No 4, RH 97%

	Th.Conductivity	Th.Diffusivity	Spec.Heat
	90^{o}C, Kapton 9,719 mm		
Measure 1	2,21	0,91	2,45
Measure 2	2,18	0,88	2,48
Measure 3	2,16	0,84	2,56
Measure 4	1,83	0,79	2,33
Measure 5	1,82	0,73	2,48
Mean value	**2,04**	**0,83**	**2,46**
C.O.V (%)	**9,8**	**8,6**	**3,3**

No 5, RH 97%

	90^{o}C, Kapton 9,719 mm		
Measure 1	2,18	0,79	2,76
Measure 2	2,22	0,82	2,70
Measure 3	2,22	0,88	2,53
Measure 4	2,22	0,84	2,63
Mean value	**2,21**	**0,83**	**2,66**
C.O.V (%)	**0,8**	**4,4**	**3,8**

No 6, RH 97%

	90^{o}C, Kapton 9,719 mm		
Measure 1	2,20	0,78	2,82
Measure 2	2,21	0,80	2,76
Measure 3	2,20	0,81	2,73
Mean value	**2,20**	**0,79**	**2,77**
C.O.V (%)	**0,2**	**1,8**	**1,7**

No 9, RH 75%

	90^{o}C, Kapton 9,719 mm		
Measure 1	2,04	0,97	2,11
Measure 2	1,98	0,92	2,15
Measure 3	1,94	0,91	2,14
Measure 4	1,76	0,88	1,99
Measure 5	1,75	0,85	2,06
Mean value	**1,89**	**0,91**	**2,09**
C.O.V (%)	**7,1**	**5,0**	**3,1**

No 22, RH 33%

	90^{o}C, Kapton 9,719 mm		
Measure 1	1,78	0,77	2,31
Measure 2	1,79	0,78	2,29
Measure 3	1,79	0,78	2,31
Measure 4	1,80	0,86	2,10
Measure 5	1,78	0,80	2,22
Measure 6	1,76	0,79	2,24
Measure 7	1,72	0,77	2,24
Mean value	**1,77**	**0,79**	**2,24**
C.O.V (%)	**1,4**	**3,9**	**3,2**

No 38, RH 0%

	90^{o}C, Kapton 9,719 mm		
Measure 1	1,62	0,70	2,29
Measure 2	1,61	0,73	2,20
Measure 3	1,61	0,73	2,20
Measure 4	1,61	0,69	2,35
Measure 5	1,62	0,71	2,27
Mean value	**1,61**	**0,71**	**2,26**
C.O.V (%)	**0,3**	**2,8**	**2,9**

No 32

	Th.Conductivity	**Th.Diffusivity**	**Spec.Heat**
	20^{o}C after drying at 105 ^{o}C, Kapton 9,719 mm		
Measure 1	1,60	0,99	1,62
Measure 2	1,61	1,03	1,56
Measure 3	1,61	1,02	1,57
Measure 4	1,59	1,02	1,55
Measure 5	1,61	0,99	1,63
Measure 6	1,60	1,07	1,50
Measure 7	1,61	1,00	1,61
Mean value	**1,60**	**1,02**	**1,58**
C.O.V (%)	**0,4**	**2,8**	**2,8**
	20^{o}C after drying at 200 ^{o}C, Kapton 9,719 mm		
Measure 1	1,53	1,02	1,50
Measure 2	1,54	1,03	1,50
Measure 3	1,56	1,04	1,49
Measure 4	1,55	1,05	1,47
Measure 5	1,55	1,04	1,49
Mean value	**1,55**	**1,04**	**1,49**
C.O.V (%)	**0,5**	**1,2**	**0,8**

No 33

	20°C after drying at 105 °C, Kapton 9,719 mm		
Measure 1	1,66	0,98	1,69
Measure 2	1,65	0,89	1,85
Measure 3	1,65	0,94	1,75
Measure 4	1,66	0,94	1,76
Measure 5	1,64	0,99	1,65
Measure 6	1,66	0,99	1,67
Measure 7	1,64	0,99	1,66
Mean value	**1,65**	**0,96**	**1,72**
C.O.V (%)	**0,5**	**3,9**	**4,2**
	20°C after drying at 200 °C, Kapton 9,719 mm		
Measure 1	1,45	0,75	1,95
Measure 2	1,44	0,80	1,79
Measure 3	1,47	0,84	1,76
Measure 4	1,47	0,76	1,93
Measure 5	1,46	0,76	1,93
Measure 6	1,45	0,74	1,96
Measure 7	1,47	0,85	1,74
Mean value	**1,46**	**0,78**	**1,87**
C.O.V (%)	**0,8**	**5,7**	**5,3**

No 34

	20°C after drying at 105 °C, Kapton 9,719 mm		
Measure 1	2,02	0,91	2,21
Measure 2	1,97	0,87	2,26
Measure 3	1,97	0,91	2,17
Measure 4	1,94	0,87	2,22
Measure 5	1,96	0,85	2,31
Measure 6	1,97	0,93	2,12
Measure 7	1,97	0,91	2,16
Mean value	**1,97**	**0,89**	**2,21**
C.O.V (%)	**1,2**	**3,3**	**3,0**
	20°C after drying at 200 °C, Kapton 9,719 mm		
Measure 1	1,18	0,57	2,07
Measure 2	1,18	0,58	2,05
Measure 3	1,18	0,56	2,10
Measure 4	1,17	0,56	2,09
Measure 5	1,17	0,57	2,07
Mean value	**1,18**	**0,57**	**2,08**
C.O.V (%)	**0,4**	**1,3**	**1,0**

High performance concrete

No 54 dried after room temperature test

	Th.Conductivity	Th.Diffusivity	Spec.Heat
	20^{o}C, Kapton 9,719 mm		
Measure 1	2,21	1,00	2,20
Measure 2	2,21	1,02	2,16
Measure 3	2,21	1,02	2,16
Measure 4	2,21	1,04	2,13
Measure 5	2,21	1,01	2,19
Mean value	**2,21**	**1,02**	**2,17**
C.O.V (%)	**0,1**	**1,2**	**1,1**
	90^{o}C, Kapton 9,719 mm		
Measure 1	1,86	0,88	2,12
Measure 2	1,87	0,89	2,09
Measure 3	1,87	0,87	2,15
Measure 4	1,86	0,84	2,22
Mean value	**1,87**	**0,87**	**2,15**
C.O.V (%)	**0,3**	**2,7**	**2,6**
	110^{o}C, Mica 6,631 mm		
Measure 1	2,60	0,86	3,03
Measure 2	2,63	0,90	2,92
Measure 3	2,64	0,83	3,19
Measure 4	2,66	0,84	3,15
Measure 5	2,62	0,85	3,07
Mean value	2,66	0,81	3,30
C.O.V (%)	**0,8**	**3,4**	**3,2**
	200^{o}C, Mica 6,631 mm		
Measure 1	2,23	0,70	3,17
Measure 2	2,22	0,68	3,24
Measure 3	2,24	0,72	3,12
Measure 4	2,22	0,69	3,20
Measure 5	2,21	0,69	3,23
Mean value	**2,22**	**0,70**	**3,19**
C.O.V (%)	**0,5**	**2,0**	**1,5**
	300^{o}C, Mica 6,631 mm		
Measure 1	1,92	0,52	3,67
Measure 2	2,03	0,92	2,20
Measurement disturbances			
Mean value	**1,97**	**0,72**	**2,94**
C.O.V (%)	**4,1**	**39,3**	**35,5**
	500^{o}C, Mica 6,631 mm		
Measure 1	1,67	0,42	3,92
Measure 2	1,62	0,44	3,71
Measure 3	1,63	0,45	3,66
Measure 4	1,59	0,44	3,61
Mean value	**1,63**	**0,44**	**3,73**
C.O.V (%)	**1,9**	**2,0**	**3,6**

	600^{o}C, Mica 6,631 mm		
Measure 1	1,59	0,38	4,15
Measure 2	1,57	0,37	4,26
Measure 3	1,57	0,37	4,22
Measure 4	1,57	0,37	4,25
Mean value	**1,58**	**0,37**	**4,22**
C.O.V (%)	**0,6**	**1,8**	**1,2**

No 46, RH 75%

	Th.Conductivity	Th.Diffusivity	Spec.Heat
	20^{o}C, Kapton 9,719 mm		
Measure 1	2,20	0,95	2,31
Measure 2	2,21	0,95	2,31
Measure 3	2,20	0,96	2,30
Measure 4	2,20	0,97	2,26
Measure 5	2,20	0,98	2,25
Mean value	**2,20**	**0,96**	**2,29**
C.O.V (%)	**0,1**	**1,3**	**1,4**

No 47, RH 75%

	20^{o}C, Kapton 9,719 mm		
Measure 1	2,14	0,87	2,46
Measure 2	2,15	0,90	2,40
Measure 3	2,15	0,90	2,37
Measure 4	2,16	0,91	2,36
Mean value	2,16	0,91	2,36
C.O.V (%)	**0,3**	**1,9**	**1,7**

No 54, RH 75%

	20^{o}C, Kapton 9,719 mm		
Measure 1	2,21	1,00	2,20
Measure 2	2,21	1,02	2,16
Measure 3	2,21	1,02	2,16
Measure 4	2,21	1,04	2,13
Measure 5	2,21	1,01	2,19
Mean value	**2,21**	**1,02**	**2,17**
C.O.V (%)	**0,1**	**1,2**	**1,1**

No 56, RH 0%

	20^{o}C, Kapton 9,719 mm		
Measure 1	1,84	1,03	1,79
Measure 2	1,84	1,07	1,73
Measure 3	1,84	1,10	1,67
Measure 4	1,84	1,04	1,78
Mean value	**1,84**	**1,06**	**1,74**
C.O.V (%)	**0,1**	**3,0**	**3,0**

No 57, RH 0%

	20°C, Kapton 9,719 mm		
Measure 1	1,96	1,03	1,91
Measure 2	1,97	1,05	1,87
Measure 3	1,97	1,03	1,90
Measure 4	1,96	1,03	1,91
Mean value	**1,96**	**1,04**	**1,90**
C.O.V (%)	**0,1**	**1,2**	**1,1**

No 58, RH 0%

	20°C, Kapton 9,719 mm		
Measure 1	1,92	0,90	2,14
Measure 2	1,94	0,94	2,07
Measure 3	1,94	0,92	2,12
Measure 4	1,96	0,98	1,99
Measure 5	1,94	0,95	2,04
Mean value	**1,94**	**0,94**	**2,07**
C.O.V (%)	**0,6**	**3,6**	**3,1**

No 61, RH 50%

	20°C, Kapton 9,719 mm		
Measure 1	2,16	0,98	2,20
Measure 2	2,17	0,99	2,20
Measure 3	2,17	0,99	2,20
Measure 4	2,15	0,96	2,25
Measure 5	2,16	0,97	2,22
Measure 6	2,16	0,97	2,23
Mean value	**2,16**	**0,98**	**2,22**
C.O.V (%)	**0,4**	**1,2**	**0,9**

No 62, RH 50%

	20°C, Kapton 9,719 mm		
Measure 1	2,25	1,21	1,86
Measure 2	2,26	1,22	1,85
Measure 3	2,25	1,25	1,79
Measure 4	2,25	1,21	1,86
Measure 5	2,25	1,21	1,86
Mean value	**2,25**	**1,22**	**1,85**
C.O.V (%)	**0,2**	**1,5**	**1,6**

Self-compacting concrete

No 75, RH 0%

	Th.Conductivity	Th.Diffusivity	Spec.Heat
	20°C, Kapton 9,719 mm		
Measure 1	1,95	0,97	2,01
Measure 2	1,97	0,96	2,05
Measure 3	1,96	0,95	2,05
Measure 4	1,97	1,00	1,98
Measure 5	1,96	0,93	2,11
Mean value	**1,96**	**0,96**	**2,04**
C.O.V (%)	**0,4**	**2,7**	**2,5**
	150°C, Mica 9,719 mm		
Measure 1	2,00	0,71	2,82
Measure 2	2,00	0,69	2,90
Measure 3	2,00	0,68	2,94
Measure 4	1,98	0,67	2,97
Mean value	**2,00**	**0,69**	**2,91**
C.O.V (%)	**0,4**	**2,6**	**2,3**
	200°C, Mica 9,719 mm		
Measure 1	1,93	0,66	2,93
Measure 2	1,92	0,68	2,84
Measure 3	1,91	0,65	2,93
Measure 4	1,88	0,60	3,11
Measure 5	1,90	0,63	3,00
Measure 6	1,90	0,63	3,00
Measure 7	1,90	0,63	3,00
Mean value	**1,91**	**0,64**	**2,97**
C.O.V (%)	**0,9**	**3,7**	**2,9**
	300°C, Mica 9,719 mm		
Measure 1	1,73	0,63	2,76
Measure 2	1,73	0,61	2,84
Measure 3	1,71	0,60	2,87
Measure 4	1,65	0,52	3,19
Measure 5	1,71	0,60	2,84
Measure 6	1,65	0,53	3,14
Measure 7	1,72	0,61	2,80
Mean value	**1,70**	**0,58**	**2,92**
C.O.V (%)	**2,0**	**7,6**	**5,9**
	500°C, Mica 9,719 mm		
Measure 1	1,43	0,38	3,74
Measure 2	1,45	0,39	3,71
Measure 3	1,44	0,40	3,65
Measure 4	1,44	0,39	3,71
Mean value	**1,44**	**0,39**	**3,70**
C.O.V (%)	**0,6**	**1,5**	**1,0**

	600°C, Mica 9,719 mm		
Measure 1	1,33	0,34	3,94
Measure 2	1,33	0,33	4,04
Measure 3	1,34	0,30	4,47
Measure 4	1,30	0,27	4,79
Mean value	**1,32**	**0,31**	**4,31**
C.O.V (%)	**1,3**	**9,7**	**9,1**

No 69 dried after room temperature test

	Th.Conductivity	Th.Diffusivity	Spec.Heat
	20°C, Kapton 9,719 mm		
Measure 1	2,24	1,00	2,25
Measure 2	2,29	1,00	2,30
Measure 3	2,25	1,02	2,21
Measure 4	2,25	1,02	2,21
Measure 5	2,26	0,97	2,33
Mean value	**2,26**	**1,00**	**2,26**
C.O.V (%)	**0,9**	**2,0**	**2,3**
	90°C, Kapton 9,719 mm		
Measure 1	1,77	0,81	2,20
Measure 2	1,80	0,83	2,16
Measure 3	1,87	0,91	2,06
Measure 4	1,87	0,88	2,12
Measure 5	1,82	0,85	2,15
Mean value	**1,83**	**0,86**	**2,14**
C.O.V (%)	**2,4**	**4,8**	**2,4**
	110°C, Mica 6.631 mm		
Measure 1	2,80	0,85	3,30
Measure 2	2,78	0,84	3,30
Measure 3	2,83	0,88	3,21
Measure 4	2,82	0,85	3,30
Mean value	**2,81**	**0,86**	**3,28**
C.O.V (%)	**0,7**	**1,9**	**1,4**
	200°C, Mica 6.631 mm		
Measure 1	2,38	0,71	3,33
Measure 2	2,33	0,74	3,16
Measure 3	2,29	0,74	3,08
Measure 4	2,35	0,65	3,63
Measure 5	2,35	0,68	3,46
Measure 6	2,32	0,60	3,85
Measure 7	2,36	0,66	3,55
Mean value	**2,34**	**0,68**	**3,44**
C.O.V (%)	**1,3**	**7,4**	**7,9**
	300°C, Mica 6.631 mm		
Measure 1	1,97	0,60	3,26
Measure 2	1,97	0,60	3,28
Measure 3	1,97	0,60	3,28
Measure 4	1,97	0,60	3,29
Mean value	**1,97**	**0,60**	**3,28**
C.O.V (%)	**0,1**	**0,3**	**0,4**

	500°C, Mica 6.631 mm		
Measure 1	1,62	0,46	3,52
Measure 2	1,62	0,45	3,57
Measure 3	1,60	0,44	3,66
Measure 4	1,61	0,46	3,49
Mean value	**1,61**	**0,45**	**3,56**
C.O.V (%)	**0,5**	**2,4**	**2,2**
	600°C, Mica 6.631 mm		
Measure 1	1,52	0,39	3,90
Measure 2	1,53	0,38	4,01
Measure 3	1,54	0,37	4,15
Measure 4	1,53	0,39	3,92
Mean value	**1,53**	**0,38**	**3,99**
C.O.V (%)	**0,7**	**2,3**	**2,8**

No 69, RH 75%

	Th.Conductivity	**Th.Diffusivity**	**Spec.Heat**
	20°C, Kapton 9,719 mm		
Measure 1	2,24	1,00	2,25
Measure 2	2,29	1,00	2,30
Measure 3	2,25	1,02	2,21
Measure 4	2,25	1,02	2,21
Measure 5	2,26	0,97	2,33
Mean value	**2,26**	**1,00**	**2,26**
C.O.V (%)	**0,9**	**2,0**	**2,3**

No 72, RH 75%

	20°C, Kapton 9,719 mm		
Measure 1	2,44	0,85	2,88
Measure 2	2,44	0,85	2,86
Measure 3	2,45	0,88	2,77
Measure 4	2,44	0,87	2,82
Measure 5	2,44	0,88	2,76
Mean value	**2,44**	**0,87**	**2,82**
C.O.V (%)	**0,1**	**1,9**	**1,9**

No 75, RH 0%

	20°C, Kapton 9,719 mm		
Measure 1	1,95	0,97	2,01
Measure 2	1,97	0,96	2,05
Measure 3	1,96	0,95	2,05
Measure 4	1,97	1,00	1,98
Measure 5	1,96	0,93	2,11
Mean value	**1,96**	**0,96**	**2,04**
C.O.V (%)	**0,4**	**2,7**	**2,5**

No 75, RH 75%

	20^{o}C, Kapton 9,719 mm		
Measure 1	2,20	0,91	2,41
Measure 2	2,21	0,95	2,33
Measure 3	2,21	0,95	2,32
Measure 4	2,21	0,95	2,33
Measure 5	2,22	0,97	2,29
Measure 6	2,22	0,96	2,30
Mean value	**2,21**	**0,95**	**2,33**
C.O.V (%)	**0,3**	**1,9**	**1,7**

No 79, RH 0%

	20^{o}C, Kapton 9,719 mm		
Measure 1	1,97	0,87	2,26
Measure 2	1,97	0,88	2,25
Measure 3	1,96	0,85	2,30
Measure 4	1,98	0,91	2,17
Measure 5	2,00	0,87	2,30
Mean value	**1,98**	**0,88**	**2,25**
C.O.V (%)	**0,8**	**2,6**	**2,3**

No 80, RH 0%

	20^{o}C, Kapton 9,719 mm		
Measure 1	1,88	0,94	2,00
Measure 2	1,89	0,96	1,96
Measure 3	1,88	0,98	1,93
Measure 4	1,89	0,96	1,96
Mean value	**1,89**	**0,96**	**1,96**
C.O.V (%)	**0,2**	**1,6**	**1,5**

No 81, RH 0%

	20^{o}C, Kapton 9,719 mm		
Measure 1	2,12	0,87	2,43
Measure 2	2,13	0,91	2,34
Measure 3	2,13	0,91	2,33
Measure 4	2,14	0,93	2,28
Measure 5	2,13	0,93	2,29
Mean value	**2,13**	**0,91**	**2,34**
C.O.V (%)	**0,2**	**2,7**	**2,5**

Cement paste

No 100, RH 0%

	Th.Conductivity	Th.Diffusivity	Spec.Heat
	20°C, Kapton 9,719 mm		
Measure 1	0,72	0,45	1,60
Measure 2	0,69	0,41	1,67
Measure 3	0,69	0,41	1,68
Measure 4	0,70	0,45	1,54
Measure 5	0,69	0,42	1,63
Mean value	**0,70**	**0,43**	**1,62**
C.O.V (%)	**1,7**	**4,7**	**3,6**
	90°C, Mica 6,631 mm		
Measure 1	0,75	0,29	2,56
Measure 2	0,74	0,30	2,47
Measure 3	0,74	0,29	2,57
Measure 4	0,75	0,30	2,46
Mean value	**0,744**	**0,30**	**2,514**
C.O.V (%)	**0,2**	**2,3**	**2,2**
	200°C, Mica 6,631 mm		
Measure 1	0,71	0,29	2,43
Measure 2	0,71	0,29	2,43
Measure 3	0,70	0,25	2,82
Measure 4	0,69	0,30	2,32
Measure 5	0,72	0,31	2,30
Measure 6	0,71	0,30	2,33
Measure 7	0,71	0,31	2,27
Mean value	**0,71**	**0,29**	**2,41**
C.O.V (%)	**1,5**	**7,6**	**7,8**
	300°C, Mica 6,631 mm		
Measure 1	0,65	0,28	2,32
Measure 2	0,62	0,24	2,58
Measure 3	0,62	0,24	2,54
Measure 4	0,63	0,24	2,57
Measure 5	0,64	0,27	2,42
Mean value	**0,63**	**0,26**	**2,49**
C.O.V (%)	**2,4**	**7,1**	**4,6**
	500°C, Mica 6,631 mm		
Measure 1	0,48	0,16	2,97
Measure 2	0,48	0,16	2,97
Measure 3	0,49	0,17	2,86
Measure 4	0,50	0,18	2,82
Mean value	**0,49**	**0,17**	**2,90**
C.O.V (%)	**1,9**	**4,6**	**2,7**
	600°C, Mica 6,631 mm		
Measure 1	0,53	0,18	2,90
Measure 2	0,49	0,15	3,22
Measure 3	0,51	0,16	3,19
Measure 4	0,52	0,18	2,92
Measure 5	0,52	0,17	3,02
Measure 6	0,53	0,18	2,89
Mean value	**0,51**	**0,17**	**3,02**
C.O.V (%)	**3,2**	**7,8**	**4,9**

	500^{o}C, Mica 6,631 mm		
Measure 1	0,50	0,19	2,58
Measure 2	0,50	0,19	2,58
Measure 3	0,50	0,19	2,66
Measure 4	0,49	0,19	2,62
Mean value	**0,49**	**0,19**	**2,61**
C.O.V (%)	**0,4**	**1,6**	**1,4**
	200^{o}C, Mica 6,631 mm		
Measure 1	0,47	0,20	2,37
Measure 2	0,47	0,19	2,41
Measure 3	0,47	0,19	2,46
Measure 4	0,47	0,20	2,32
Mean value	**0,47**	**0,20**	**2,39**
C.O.V (%)	**0,2**	**2,6**	**2,5**
	20^{o}C, Mica 6,631 mm		
Measure 1	0,37	0,28	1,34
Measure 2	0,38	0,29	1,30
Measure 3	0,38	0,30	1,28
Measure 4	0,38	0,30	1,29
Mean value	**0,38**	**0,29**	**1,30**
C.O.V (%)	**1,3**	**3,2**	**2,1**

Spruce

Hig density spruce

	Ax.Th.Conductivity	Ax.Th.Diffusivity	Rad.Th.Conductivity	Rad.Th.Diffusivity
	20^oC, Kapton 9,719 mm, Specific heat 0.74			
Measure 1	0,55	0,74	0,11	0,14
Measure 2	0,56	0,75	0,11	0,14
Measure 3	0,56	0,75	0,11	0,14
Measure 4	0,56	0,76	0,11	0,15
Measure 5	0,57	0,77	0,11	0,15
Mean value	**0,56**	**0,76**	**0,11**	**0,15**
C.O.V (%)	**1,2**	**1,2**	**1,4**	**1,4**
	110^oC, Kapton 9,719 mm, Specific heat 1.14			
Measure 1	0,42	0,37	0,15	0,13
Measure 2	0,41	0,36	0,15	0,13
Measure 3	0,44	0,39	0,13	0,11
Mean value	**0,43**	**0,37**	**0,14**	**0,12**
C.O.V (%)	**3,8**	**3,8**	**8,2**	**8,2**
	150^oC, Kapton 9,719 mm, Specific heat 1.21			
Measure 1	0,52	0,43	0,12	0,10
Measure 2	0,54	0,45	0,10	0,08
Measure 3	0,51	0,42	0,13	0,10
Mean value	**0,53**	**0,43**	**0,12**	**0,10**
C.O.V (%)	**2,8**	**2,8**	**13,4**	**13,4**

Low density spruce

	Ax.Th.Conductivity	Ax.Th.Diffusivity	Rad.Th.Conductivity	Rad.Th.Diffusivity
	20^oC, Kapton 9,719 mm, Specific heat 0.612			
Measure 1	0,24	0,39	0,12	0,20
Measure 2	0,25	0,40	0,11	0,18
Measure 3	0,26	0,42	0,10	0,16
Measure 4	0,24	0,40	0,11	0,18
Mean value	**0,246**	**0,40**	**0,111**	**0,182**
C.O.V (%)	**3,6**	**3,6**	**9,5**	**9,5**
	90^oC, Kapton 9,719 mm, Specific heat 0.7			
Measure 1	0,35	0,50	0,10	0,15
Measure 2	0,41	0,59	0,08	0,11
Measure 3	0,42	0,60	0,09	0,13
Measure 4	0,23	0,33	0,15	0,22
Mean value	**0,354**	**0,51**	**0,107**	**0,153**
C.O.V (%)	**24,7**	**24,7**	**31,8**	**31,8**
	110^oC, Kapton 9,719 mm, Specific heat 0.78			
Measure 1	0,27	0,34	0,16	0,21
Measure 2	0,37	0,48	0,09	0,12
Measure 3	0,28	0,36	0,12	0,16
Measure 4	0,32	0,41	0,10	0,13
Measure 5	0,35	0,45	0,07	0,09
Measure 6	0,29	0,37	0,15	0,19
Measure 7	0,28	0,36	0,14	0,18
Mean value	**0,308**	**0,39**	**0,120**	**0,154**
C.O.V (%)	**13,7**	**13,7**	**27,5**	**27,5**

	150°C, Kapton 9,719 mm, Specific heat 0.83			
Measure 1	0,33	0,40	0,11	0,13
Measure 2	0,38	0,46	0,06	0,07
Measure 3	0,44	0,53	0,08	0,10
Measure 4	0,43	0,52	0,07	0,08
Measure 5	0,28	0,34	0,14	0,17
Mean value	**0,373**	**0,45**	**0,091**	**0,110**
C.O.V (%)	**18,4**	**18,4**	**35,2**	**35,2**

Particleboard

Dry	**Th.Conductivity**	**Th.Diffusivity**	**Spec.Heat**
	23°C, Kapton 6.403 mm		
Measure 1	0,17	0,18	0,95
Measure 2	0,17	0,17	0,96
Measure 3	0,17	0,18	0,94
Measure 4	0,16	0,18	0,89
Measure 5	0,16	0,18	0,87
Measure 6	0,16	0,18	0,89
Mean value	**0,16**	**0,18**	**0,92**
C.O.V. (%)	**2,20**	**2,16**	**4,13**
	75°C, Kapton 6.403 mm		
Measure 1	0,18	0,16	1,11
Measure 2	0,18	0,17	1,10
Measure 3	0,19	0,16	1,19
Measure 4	0,19	0,17	1,15
Measure 5	0,18	0,16	1,17
Measure 6	0,19	0,16	1,17
Mean value	**0,19**	**0,16**	**1,15**
C.O.V. (%)	**1,79**	**2,82**	**3,41**
	105°C, Kapton 6.403 mm		
Measure 1	0,19	0,15	1,26
Measure 2	0,20	0,17	1,16
Measure 3	0,19	0,16	1,20
Measure 4	0,19	0,15	1,29
Measure 5	0,19	0,15	1,28
Measure 6	0,19	0,15	1,27
Mean value	**0,19**	**0,15**	**1,24**
C.O.V. (%)	**1,61**	**5,71**	**4,02**
	150°C, Kapton 6.403 mm		
Measure 1	0,18	0,12	1,48
Measure 2	0,18	0,12	1,49
Measure 3	0,18	0,13	1,40
Measure 4	0,18	0,12	1,47
Measure 5	0,18	0,11	1,72
Measure 6	0,19	0,13	1,48
Measure 7	0,19	0,12	1,58
Mean value	**0,18**	**0,12**	**1,52**
C.O.V. (%)	**2,10**	**7,04**	**6,76**

	190^{o}C, Kapton 6.403 mm		
Measure 1	0,16	0,09	1,69
Measure 2	0,16	0,08	2,00
Measure 3	0,14	0,08	1,83
Measure 4	0,14	0,07	2,10
Measure 5	0,12	0,05	2,25
Measure 6	0,12	0,06	2,21
Mean value	**0,14**	**0,07**	**2,01**
C.O.V. (%)	**10,76**	**20,89**	**10,84**

Moist (7%)

	23^{o}C, Kapton 6.403 mm		
Measure 1	0,18	0,17	1,02
Measure 2	0,18	0,17	1,03
Measure 3	0,18	0,17	1,03
Mean value	**0,18**	**0,17**	**1,03**
C.O.V. (%)	**0,78**	**1,49**	**0,73**

Fibreboard

Dry	**Th.Conductivity**	**Th.Diffusivity**	**Spec.Heat**
	23^{o}C, Kapton 6.403 mm		
Measure 1	0,09	0,33	0,26
Measure 2	0,09	0,33	0,27
Measure 3	0,09	0,32	0,28
Measure 4	0,09	0,32	0,28
Mean value	**0,09**	**0,32**	**0,27**
C.O.V. (%)	**1,99**	**1,94**	**3,92**
	75^{o}C, Kapton 6.403 mm		
Measure 1	0,10	0,22	0,47
Measure 2	0,10	0,23	0,45
Measure 3	0,11	0,25	0,43
Mean value	**0,10**	**0,23**	**0,45**
C.O.V. (%)	**2,73**	**6,66**	**3,85**
	105^{o}C, Kapton 6.403 mm		
Measure 1	0,11	0,24	0,44
Measure 2	0,11	0,25	0,42
Measure 3	0,10	0,25	0,41
Measure 4	0,11	0,25	0,43
Measure 5	0,10	0,21	0,47
Measure 6	0,10	0,22	0,47
Measure 7	0,11	0,24	0,45
Mean value	**0,10**	**0,24**	**0,44**
C.O.V. (%)	**1,80**	**6,70**	**5,64**

	150^{o}C, Kapton 6.403 mm		
Measure 1	0,10	0,22	0,48
Measure 2	0,10	0,20	0,49
Measure 3	0,11	0,23	0,46
Mean value	**0,10**	**0,22**	**0,48**
C.O.V. (%)	**4,15**	**7,02**	**2,99**
	190^{o}C, Kapton 6.403 mm		
Measure 1	0,10	0,18	0,57
Measure 2	0,11	0,21	0,51
Measure 3	0,10	0,16	0,59
Mean value	**0,10**	**0,18**	**0,56**

Moist (7%)	**Th.Conductivity**	**Th.Diffusivity**	**Spec.Heat**
	23^{o}C, Kapton 6.403 mm		
Measure 1	0,10	0,29	0,36
Measure 2	0,10	0,29	0,36
Measure 3	0,10	0,28	0,37
Measure 4	0,10	0,31	0,32
Measure 5	0,10	0,30	0,32
Measure 6	0,10	0,30	0,33
Mean value	**0,10**	**0,29**	**0,34**
C.O.V. (%)	**2,80**	**3,69**	**6,33**

Polymethylmetacrylate (PMMA)

	Th.Conductivity	**Th.Diffusivity**	**Spec.Heat**
	23^{o}C, Kapton 6.403 mm		
Measure 1	0,2101	0,1152	1,8235
Measure 2	0,2090	0,1133	1,8450
Measure 3	0,2086	0,1146	1,8207
Measure 4	0,2061	0,1084	1,9016
Measure 5	0,216	0,121	1,792
Measure 6	0,216	0,118	1,825
Measure 7	0,220	0,116	1,907
Mean value	**0,212**	**0,115**	**1,845**
C.O.V. (%)	**2,4**	**3,3**	**2,3**
	53^{o}C, Kapton 6.403 mm		
Measure 1	0,201	0,098	2,055
Measure 2	0,203	0,104	1,958
Mean value	**0,202**	**0,101**	**2,006**
C.O.V. (%)	**0,5**	**3,9**	**3,4**
	77^{o}C, Kapton 6.403 mm		
Measure 1	0,199	0,093	2,149
Measure 2	0,202	0,097	2,088
Measure 3	0,203	0,098	2,080
Mean value	**0,202**	**0,096**	**2,106**
C.O.V. (%)	**1,0**	**2,8**	**1,8**

Polystyrene

	Th.Conductivity	Th.Diffusivity	Spec.Heat
	20^{o}C, Kapton 9,719 mm		
Measure 1	0,038	1,29	0,030
Measure 2	0,038	1,29	0,030
Measure 3	0,039	1,38	0,028
Measure 4	0,038	1,42	0,027
Measure 5	0,039	1,52	0,025
Measure 6	0,039	1,54	0,025
Measure 7	0,039	1,46	0,027
Measure 8	0,039	1,46	0,026
Mean value	**0,038**	**1,42**	**0,027**
C.O.V. (%)	**0,5**	**6,7**	**6,6**
	85^{o}C, Kapton 9,719 mm		
Measure 1	0,049	1,64	0,030
Measure 2	0,048	1,62	0,030
Measure 3	0,048	1,52	0,032
Measure 4	0,048	1,45	0,033
Measure 5	0,048	1,58	0,031
Measure 6	0,048	1,43	0,034
Measure 7	0,048	1,44	0,034
Mean value	**0,048**	**1,53**	**0,032**
C.O.V. (%)	**0,3**	**5,9**	**5,6**

Polyurethane

	Th.Conductivity	Th.Diffusivity	Spec.Heat
	20^{o}C, Kapton 9,719 mm		
Measure 1	0,043	0,42	0,10
Measure 2	0,043	0,34	0,13
Measure 3	0,042	0,39	0,11
Measure 4	0,042	0,38	0,11
Measure 5	0,042	0,37	0,11
Measure 6	0,042	0,34	0,12
Mean value	**0,042**	**0,37**	**0,114**
C.O.V (%)	**1,5**	**8,0**	**7,4**
	85^{o}C, Kapton 9,719 mm		
Measure 1	0,051	1,11	0,046
Measure 2	0,051	1,23	0,042
Measure 3	0,052	1,20	0,043
Measure 4	0,051	1,18	0,043
Measure 5	0,051	1,20	0,043
Measure 6	0,051	1,23	0,041
Measure 7	0,051	1,14	0,045
Mean value	**0,051**	**1,18**	**0,043**
C.O.V (%)	**0,5**	**3,7**	**4,0**

High-density glass wool

	Th.Conductivity	Th.Diffusivity	Spec.Heat
	20^{o}C, Kapton 9,719 mm		
Measure 1	0,047	0,40	0,12
Measure 2	0,044	0,32	0,14
Measure 3	0,045	0,35	0,13
Measure 4	0,047	0,50	0,09
Mean value	**0,046**	**0,39**	**0,119**
C.O.V. (%)	**3,5**	**20,1**	**15,8**
	150^{o}C, Mica 9,719 mm		
Measure 1	0,085	0,68	0,12
Measure 2	0,077	0,36	0,21
Measure 3	0,076	0,36	0,21
Mean value	**0,079**	**0,47**	**0,184**
C.O.V. (%)	**5,9**	**40,0**	**28,1**
	200^{o}C, Mica 9,719 mm		
Measure 1	0,082	0,34	0,24
Measure 2	0,082	0,36	0,23
Measure 3	0,083	0,36	0,23
Mean value	**0,082**	**0,36**	**0,232**
C.O.V. (%)	**0,4**	**2,8**	**2,5**
	300^{o}C, Mica 9,719 mm		
Measure 1	0,10	0,50	0,20
Measure 2	0,10	0,55	0,18
Measure 3	0,10	0,70	0,15
Mean value	**0,100**	**0,58**	**0,175**
C.O.V. (%)	**1,9**	**17,4**	**14,8**
	500^{o}C, Mica 9,719 mm		
Measure 1	0,15	1,45	0,11
Measure 2	0,18	1,47	0,12
Measure 3	0,16	2,01	0,08
Mean value	**0,163**	**1,65**	**0,102**
C.O.V. (%)	**9,0**	**19,4**	**21,9**

Low-density glass wool

	Th.Conductivity	Th.Diffusivity	Spec.Heat
	20^{o}C, Kapton 9,719 mm		
Measure 1	0,041	1,21	0,034
Measure 2	0,046	1,64	0,028
Measure 3	0,040	1,16	0,035
Mean value	**0,042**	**1,34**	**0,032**
C.O.V. (%)	**7,8**	**19,9**	**11,0**
	90^{o}C, Kapton 9,719 mm		
Measure 1	0,053	2,25	0,023
Measure 2	0,052	2,59	0,020
Measure 3	0,052	2,51	0,021
Measure 4	0,052	2,52	0,021
Measure 5	0,052	2,36	0,022
Mean value	**0,052**	**2,448**	**0,021**
C.O.V. (%)	**0,5**	**5,6**	**6,1**
	150^{o}C, Kapton 9,719 mm		
Measure 1	0,066	3,26	0,020
Measure 2	0,065	2,35	0,028
Measure 3	0,065	3,21	0,020
Measure 4	0,066	3,12	0,021
Measure 5	0,066	2,50	0,026
Mean value	**0,066**	**2,89**	**0,023**
C.O.V. (%)	**0,9**	**14,8**	**15,2**
	195^{o}C, Kapton 9,719 mm		
Measure 1	0,087	3,98	0,022
Measure 2	0,085	3,15	0,027
Measure 3	0,088	3,76	0,023
Measure 4	0,087	4,15	0,021
Mean value	**0,087**	**3,76**	**0,023**
C.O.V. (%)	**1,6**	**11,7**	**11,4**
	200^{o}C, Mica 9,719 mm		
Measure 1	0,11	2,62	0,041
Measure 2	0,11	2,50	0,044
Measure 3	0,11	2,51	0,044
Mean value	**0,109**	**2,54**	**0,043**
C.O.V. (%)	**0,6**	**2,6**	**2,9**
	400^{o}C, Mica 9,719 mm		
Measure 1	0,21	8,06	0,026
Measure 2	0,21	7,87	0,026
Measure 3	0,21	8,34	0,025
Mean value	**0,208**	**8,09**	**0,026**
C.O.V. (%)	**0,6**	**2,9**	**3,4**

Low-density mineral wool

	Th.Conductivity	Th.Diffusivity	Spec.Heat
	20°C, Kapton 6,631 mm		
Measure 1	0,042	1,37	0,031
Measure 2	0,042	1,29	0,032
Measure 3	0,042	1,43	0,029
Measure 4	0,042	1,45	0,029
Mean value	**0,042**	**1,39**	**0,030**
C.O.V. (%)	**0,4**	**5,0**	**5,0**
	90°C, Kapton 6,631 mm		
Measure 1	0,053	1,69	0,032
Measure 2	0,053	1,66	0,032
Measure 3	0,053	1,70	0,031
Mean value	**0,053**	**1,69**	**0,031**
C.O.V. (%)	**0,5**	**1,2**	**1,0**
	110°C, Kapton 6,631 mm		
Measure 1	0,057	1,79	0,032
Measure 2	0,057	1,80	0,032
Measure 3	0,057	1,82	0,031
Mean value	**0,057**	**1,80**	**0,032**
C.O.V. (%)	**0,5**	**0,7**	**0,8**

	Th.Conductivity	Th.Diffusivity	Spec.Heat
	20°C, Mica 6,631 mm		
Measure 1	0,064	0,53	0,12
Measure 2	0,063	0,53	0,12
Measure 3	0,063	0,53	0,12
Mean value	**0,063**	**0,53**	**0,120**
C.O.V. (%)	**0,4**	**0,4**	**0,6**
	90°C, Mica 6,631 mm		
Measure 1	0,075	0,68	0,11
Measure 2	0,075	0,70	0,11
Measure 3	0,076	0,69	0,11
Mean value	**0,075**	**0,69**	**0,109**
C.O.V. (%)	**0,5**	**1,0**	**1,2**
	110°C, Mica 6,631 mm		
Measure 1	0,080	0,75	0,11
Measure 2	0,080	0,76	0,10
Measure 3	0,079	0,75	0,11
Mean value	**0,080**	**0,76**	**0,105**
C.O.V. (%)	**0,2**	**0,9**	**1,0**
	200°C, Mica 6,631 mm		
Measure 1	0,10	0,97	0,11
Measure 2	0,10	0,96	0,11
Measure 3	0,10	0,99	0,11
Mean value	**0,104**	**0,97**	**0,107**
C.O.V. (%)	**0,7**	**1,8**	**1,5**

	300^oC, Mica 6,631 mm		
Measure 1	0,14	1,60	0,086
Measure 2	0,14	1,63	0,084
Measure 3	0,14	2,00	0,072
Mean value	**0,140**	**1,74**	**0,081**
C.O.V. (%)	**2,5**	**12,6**	**9,4**
	500^oC, Mica 6,631 mm		
Measure 1	0,27	2,59	0,10
Measure 2	0,27	2,65	0,10
Measure 3	0,27	2,68	0,10
Mean value	**0,269**	**2,64**	**0,102**
C.O.V. (%)	**0,9**	**1,7**	**2,6**
	600^oC, Mica 6,631 mm		
Measure 1	0,35	3,48	0,10
Measure 2	0,36	3,49	0,10
Measure 3	0,37	2,95	0,12
Mean value	**0,36**	**3,31**	**0,11**
C.O.V. (%)	**2,5**	**9,5**	**12,4**

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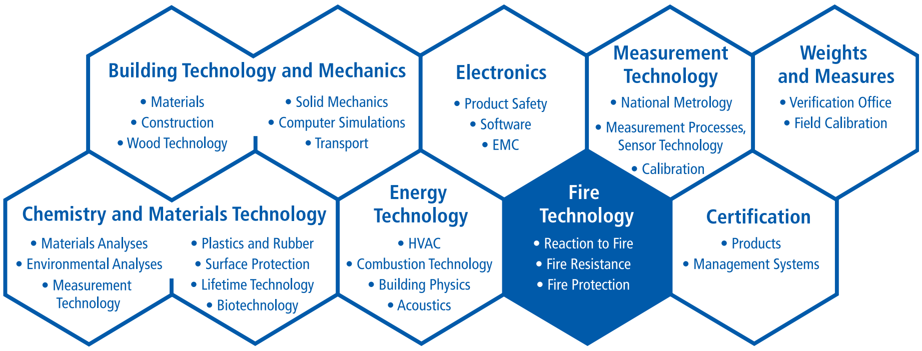

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