P-04-162

# Forsmark site investigation

# Drill hole KFM03A

# Thermal properties: heat conductivity and heat capacity determined using the TPS method and mineralogical composition by modal analysis

Bijan Adl-Zarrabi
SP Swedish National Testing and Research Institute

June 2004

**Svensk Kärnbränslehantering AB**
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

ISSN 1651-4416
SKB P-04-162

# Forsmark site investigation

# Drill hole KFM03A

# Thermal properties: heat conductivity and heat capacity determined using the TPS method and mineralogical composition by modal analysis

Bijan Adl-Zarrabi
SP Swedish National Testing and Research Institute

June 2004

*Keywords:* AP PF 400-04-20, Field note no Forsmark 215, Thermal properties, Rock mechanics, Thermal conductivity, Thermal diffusivity, Heat capacity, Transient Plane Source method, Modal analysis.

# Abstract

Thermal properties on fifteen specimens of drill hole KFM03A, Forsmark, were measured at ambient and elevated temperature. The rock type of all samples are Tonalite and Granite-granodiorite. The mineralogical content was determined by using modal analysis.

The determination of the thermal properties are based on a direct measurement method, the so called “Transient Plane Source Method (TPS)”, Gustafsson (1991) /1/.

Generally, the influence of temperature on the thermal diffusivity was greater than on the conductivity. Thermal conductivity at 20 °C was in the range of 2.46-2.81 W/(m, K) for Tonalite and 3.43-3.83 W/(m, K) for Granite-granodiorite respectively. Thermal diffusivity at 20 °C was in the range of 1.14-1.29 $mm^2/s$ for Tonalite and 1.50-1.82 $mm^2/s$ for Granite-granodiorite respectively. At 80 °C, thermal conductivity and thermal diffusivity of specimens were in the range of 3.28-3.61 W/(m, K) and 1.22-1.45 $mm^2/s$ respectively.

# Contents

# 1 Introduction

The objective of this investigation was to measure thermal properties of borehole KFM03A, Forsmark, see Figure 1-1, at different temperature levels by using the TPS-method /1/. The thermal properties were determined for water-saturated specimens. The specimens, in form of circular discs, were cut from rock cores. The samples were selected based on the preliminary core logging, and with the strategy to primarily investigate the properties of the dominant rock types. The principle of the TPS method is to place a sensor between two rock samples. The sensor consists of a thin metal double spiral, embedded in an insulation material. During the measurement the sensor works both as a heat emitter and a heat receptor. The input data and results of the direct measurement are registered and analysed by the same software and electronics that govern the measurement. The method gives information on the heat conductivity and diffusivity of a material and from this the volumetric heat capacity can be determined, if the density is known.

The test programme follows the activity plan AP PF 400-04-20 (SKB internal controlling document) and is controlled by SP-QD 13.1 (SP quality document).

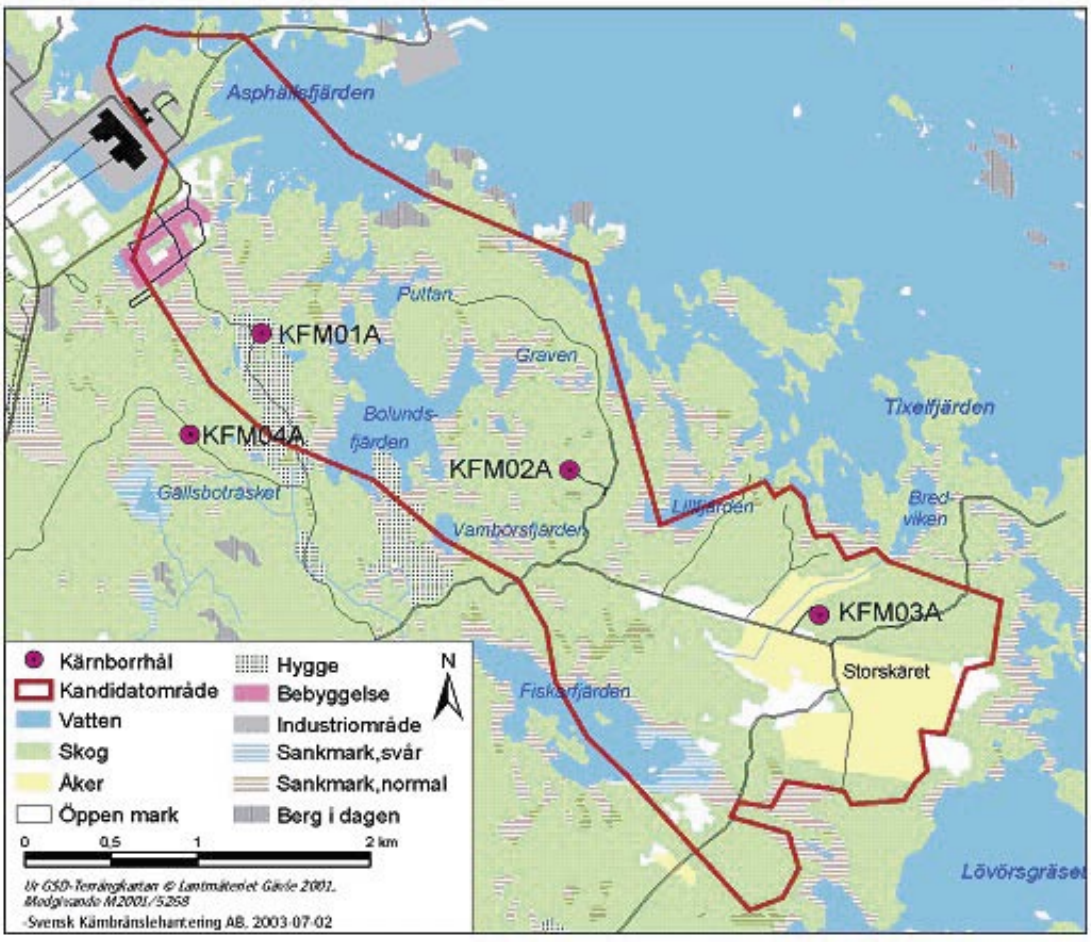


***Figure 1-1.*** *Location of the drill hole KFM03A at the Forsmark site.*

The samples were water saturated and stored in this condition for 7 days. This yields complete water saturation, whereupon the density and the thermal properties were determined. The specimens were photographed before testing.

Modal analyses, based on point counting using a polarising microscope were performed on 6 specimens that were sampled on the same level as the specimens for thermal properties.

The rock cores arrived to SP in October 2003. The testing was performed during April-May 2004.

Determination of thermal properties was made in accordance with SKB's method description SKB MD 191.001, version 1.9 (SKB internal controlling document) at the department of Fire Technology at SP. Density was determined in compliance with SKB MD 160.002, version 1.9 (SKB internal controlling document) at the department of Building Technology at SP.

Modal analyses were performed according to SKB MD 160.001 (SKB internal controlling document) and BMm-P54 (SP quality document).

# 2 Objective and scope

The purpose of the testing is to determine the thermal properties of rock specimens. The results shall be used for the site descriptive modelling of thermal properties, which will be established for the candidate area selected for site investigations at Forsmark.

The samples are from the borehole KFM03A in Forsmark. The specimens were sampled on four levels in the drill hole: 260 m, 305 m, 525 m, and 685 m. The investigated rock types are mapped as Tonalite to Granodiorite (rock code 101054) at 260 m, Granite, Granodiorite and Tonalite (rock code 101051) at 305 m, and Metagranite-granodiorite (rock code 101057) at 525 m, and 685 m.

# 3 Equipment

Technical devices used for determination of thermal properties were:

- Kapton sensor 5501, radius of the sensor was 6.403 mm, and output of power was 0.7 W. The sensor 5501 fulfils the recommended relation between the radius of sensor and geometry of the samples in /2/.
- TPS-apparatus, Source meter Keithley 2400, Multi-meter Keithley 2000 and bridge, see Figure 3-1.
- PC + Microsoft Office and Hot Disk version 5.4.
- Stainless Sample holder.
- Water bath with immersion heater.
- Immersion heater, Grant, type TD. The accuracy of the thermostat is 0.004 °C.
- Hand instrument for control measuring of the water bath temperature.

Technical devices used for modal analyses (point counting) were:

- Leitz Orthoplan optical microscope (inv nr 100276).

Specimen mounting is shown in Figure 3-2.

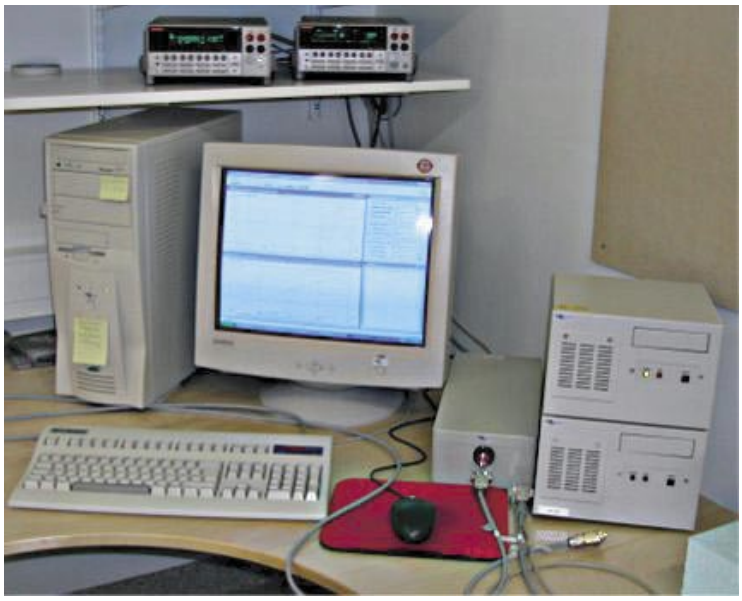

***Figure 3-1.*** *TPS-apparatus with source meter, multi-meter, bridge, and computer.*

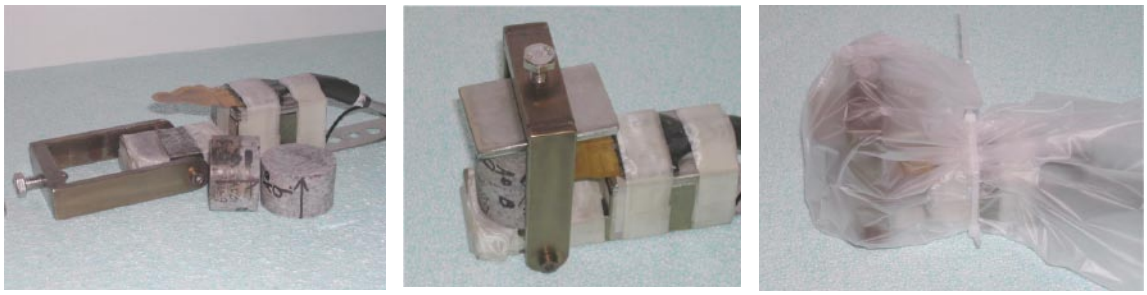

***Figure 3-2.*** *Specimens prior to mounting (left), mounted in stainless sample holder (middle), and sample holder with mounted specimens wrapped in plastic (right).*

# 4 Execution

Determination of thermal properties was made in accordance with SKB's method description SKB MD 191.001, version 1.9 (SKB internal controlling document) and Hot Disc Instruction Manual /2/ at the department of Fire Technology at SP.

Density was determined according to SKB MD 160.002, version 1.9 (SKB internal controlling document) and ISRM /3/. Modal analysis was determined in compliance with SKB MD 160.001 (SKB internal controlling document) at the department of Building Technology at SP.

## 4.1 Description of the samples

Twelve cores were sampled from three levels of drill hole KFM03A, Forsmark, Sweden. The first level was between 262.4 m and 262.6 m, the second level between 305.7 m and 305.9 m, the third level between 527.3 m and 527.7 m, and the fourth level between 683.8 m and 685.1 m. The twenty-four specimens, with a thickness of 25 mm each, were selected from the samples at SP, see Figure 3-2. The diameter of the specimens was 50 mm. The rock type, identification marks and depth of the specimens are presented in Table 4-1. Detailed geological description of the rock is given in SKB's BOREMAP of KFM03A and in the SICADA database at SKB.

Shortened sample identification F03A-90V has been used throughout the report.

**Table 4-1. Rock type and identification marks (Rock-type classification according to Boremap).**

| Identification | Rock type | Sampling depth (Sec low) |
|---|---|---|
| KFM03A-90V-1 | Tonalite to Granodiorite | 262.39 |
| KFM03A-90V-2 | Tonalite to Granodiorite | 262.45 |
| KFM03A-90V-3 | Tonalite to Granodiorite | 262.51 |
| KFM03A-90V-4 | Granodiorite-Tonalite | 305.69 |
| KFM03A-90V-5 | Granodiorite-Tonalite | 305.75 |
| KFM03A-90V-6 | Granodiorite-Tonalite | 305.82 |
| KFM03A-90V-7 | Granite-Granodiorite | 527.3 |
| KFM03A-90V-8 | Granite-Granodiorite | 527.36 |
| KFM03A-90V-9 | Granite-Granodiorite | 527.42 |
| KFM03A-90V-13 | Granite-Granodiorite | 683.77 |
| KFM03A-90V-14 | Granite-Granodiorite | 683.84 |
| KFM03A-90V-15 | Granite-Granodiorite | 683.9 |

## 4.2 Test Procedure

### 4.2.1 Thermal properties

The following steps were performed:

1. Samples were cut and polished by SP Building Technology.
2. Samples were photographed by SP Building Technology.
3. Samples were water saturated and wet density was determined by SP Building Technology.
4. Samples were sent from SP Building Technology to SP Fire Technology.
5. Thermal properties were determined.
6. Samples were sent from SP Fire Technology to SP Building Technology.
7. Dry density of samples was determined at SP Building Technology.

Thermal properties of water-saturated specimens were measured in ambient air (20 °C) as well as at 50 °C and 80 °C. In order to remain water saturation and obtain desired temperature, the samples and the sensor were kept in a plastic bag during the measurement, see Figure 3-2.

Each core pair was measured five times. The time lag between two repeated measurements was at least 20 minutes. The result of each measurement was evaluated separately. The average value of these five measurements was calculated.

Function control of TPS instrumentation was performed according to BRk-QB-M26-02 (SP quality document), see Appendix A.

Measured raw data were saved as text files. Analysed data were saved as Excel files. These files were stored on the hard disc of the measurement computer and the stored files were sent to the SKB catalogue at the SP network. Further calculations of mean values and standard deviations were performed in the same catalogue.

Thermal properties, density and porosity measurements were performed during May 2004.

Dry weight was measured after the specimens had been dried to constant mass according to ISRM /3/ at 105 °C. The drying procedure took seven days.

### 4.2.2 Modal analysis

Modal analysis, based on point counting with at least 500 points counted in each sample, was performed by SP Building Technology.

The analysis was conducted on 6 specimens that were sampled on the same level as the specimens for thermal properties (see Sec low in Table 1-1). The modal analysis was done in order to calculate the thermal properties based on the specimen's mineralogical composition.

# 5 Results

## 5.1 Thermal properties

Mean values of measured data, five repeated measurements, are reported in 5.1.1 and 5.1.2 and in the SICADA database (field note no Forsmark 215) at SKB. Values of each separate measurement as described in 4.2 are reported in Appendix B. Furthermore, the total measuring time, the ratio between total measuring time and characteristic time, and the number of analysed points are presented in Appendix C. In a correct measurement the ratio between the total measuring time and the characteristic time should be between 0.4 and 1.

### 5.1.1 Test results, sample by sample

***Sample F03A-90V-01***

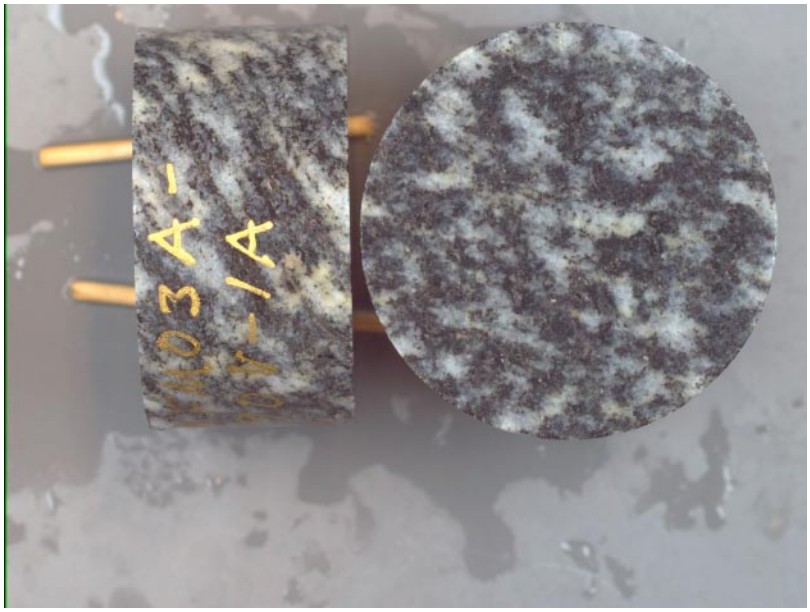


***Figure 5-1.*** *Specimens F03A-90V-01.*

**Table 5-1. Porosity, wet and dry density of specimens F03A-90V-01, average values.**

| Sample | Density, wet (kg/m³) | Density, dry (kg/m³) | Porosity (%) |
|---|---|---|---|
| F03A-90V-01 | | | |
| Sec low: 262.39 | 2766 | 2763 | 0.27 |

**Table 5-2. Thermal properties of sample F03A-90V-01 at ambient temperature.**

| F03A-90V-01<br>Sec low: 262.39 | Conductivity<br>(W/(m, K)) | Diffusivity<br>(mm²/s) | Heat capacity<br>(MJ/(m³· K)) |
|---|---|---|---|
| | 20 °C | | |
| Mean value | 2.64 | 1.29 | 2.05 |
| Standard deviation | 0.002 | 0.003 | 0.005 |

### *Sample F03A-90V-02*

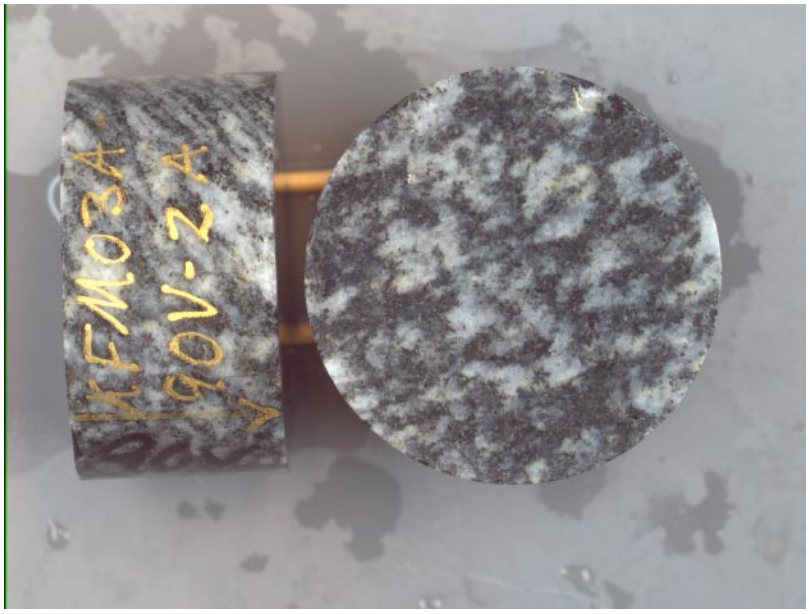


***Figure 5-2.*** *Specimens F03A-90V-02.*

**Table 5-3. Porosity, wet and dry density of specimens F03A-90V-02, average values.**

| Sample | Density, wet (kg/m³) | Density, dry (kg/m³) | Porosity (%) |
|---|---|---|---|
| F03A-90V-02 | 2777 | 2774 | 0.27 |
| Sec low: 262.45 | | | |

**Table 5-4. Thermal properties of sample F03A-90V-02 at ambient temperature.**

| F03A-90V-02<br>Sec low: 262.45 | Conductivity<br>(W/(m, K)) | Diffusivity<br>(mm²/s) | Heat capacity<br>(MJ/(m³, K)) |
|---|---|---|---|
| | 20 °C | | |
| Mean value | 2.80 | 1.24 | 2.26 |
| Standard deviation | 0.004 | 0.005 | 0.011 |

### *Sample F03A-90V-03*

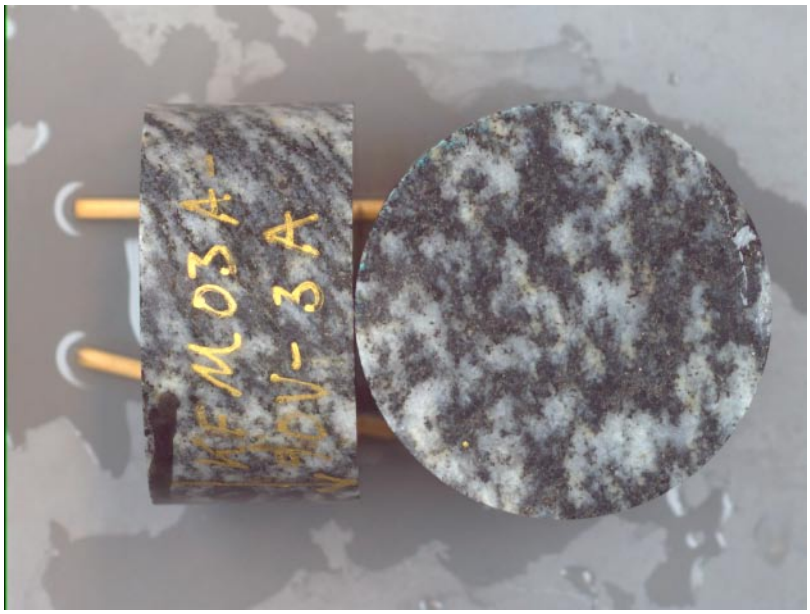

***Figure 5-3.*** *Specimens F03A-90V-03.*

**Table 5-5. Porosity, wet and dry density of specimens F03A-90V-03, average values.**

| Sample | Density, wet (kg/m$^3$) | Density, dry (kg/m$^3$) | Porosity (%) |
|---|---|---|---|
| F03A-90V-03 | | | |
| Sec low: 262.51 | 2758 | 2755 | 0.27 |

**Table 5-6. Thermal properties of sample F03A-90V-03 at ambient temperature.**

| F03A-90V-03<br>Sec low: 262.51 | Conductivity<br>(W/(m, K)) | Diffusivity<br>(mm$^2$/s) | Heat capacity<br>(MJ/(m$^3$, K)) |
|---|---|---|---|
| | 20 °C | | |
| Mean value | 2.81 | 1.18 | 2.39 |
| Standard deviation | 0.002 | 0.001 | 0.003 |

### *Sample F03A-90V-04*

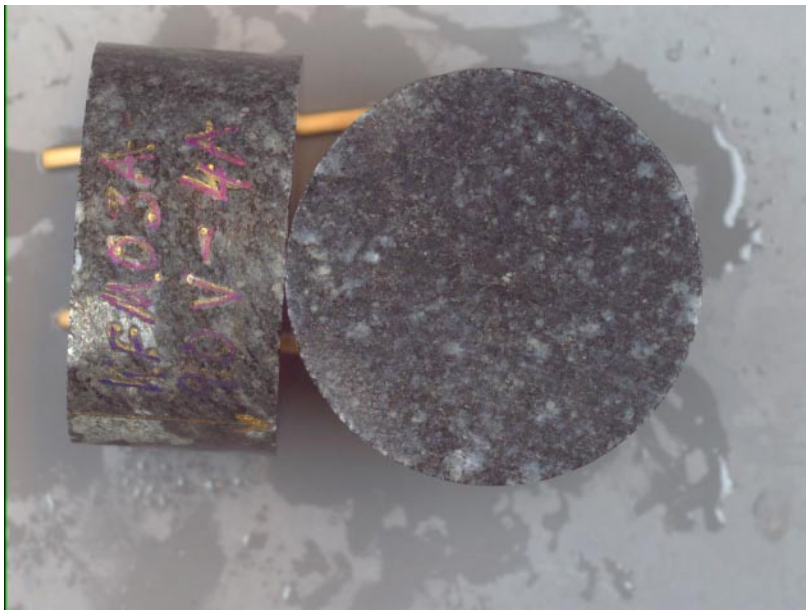

***Figure 5-4.*** *Specimens F03A-90V-04.*

**Table 5-7. Porosity, wet and dry density of specimens F03A-90V-04, average values.**

| Sample | Density, wet (kg/m$^3$) | Density, dry (kg/m$^3$) | Porosity (%) |
|---|---|---|---|
| F03A-90V-04 | | | |
| Sec low: 305.69 | 2815 | 2813 | 0.28 |

**Table 5-8. Thermal properties of sample F03A-90V-04 at ambient temperature.**

| F03A-90V-04 | Conductivity | Diffusivity | Heat capacity |
|---|---|---|---|
| Sec low: 305.69 | (W/(m, K)) | (mm$^2$/s) | (MJ/(m$^3$, K)) |
| | | 20 °C | |
| Mean value | 2.46 | 1.16 | 2.13 |
| Standard deviation | 0.002 | 0.003 | 0.005 |

### *Sample F03A-90V-05*

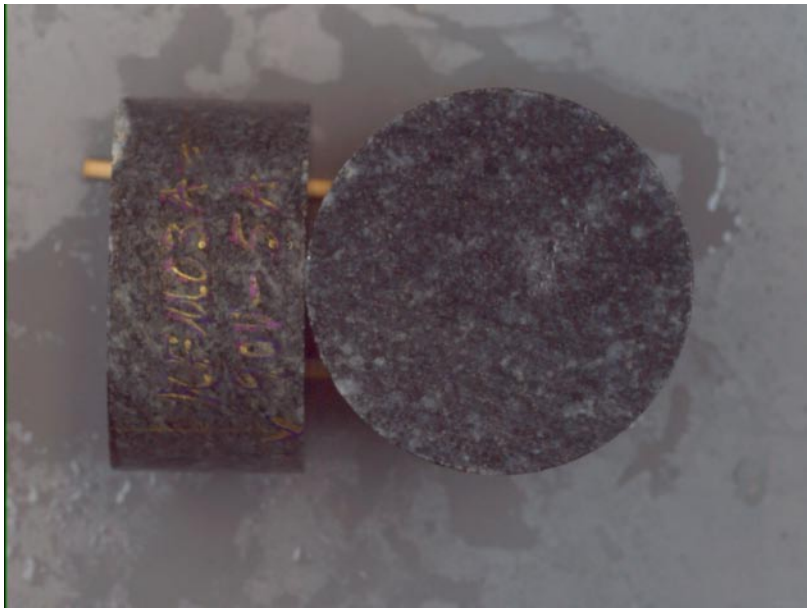

***Figure 5-5.*** *Specimens F03A-90V-05.*

**Table 5-9. Porosity, wet and dry density of specimens F03A-90V-05, average values.**

| Sample | Density, wet (kg/m$^3$) | Density, dry (kg/m$^3$) | Porosity (%) |
|---|---|---|---|
| F03A-90V-05 | | | |
| Sec low: 305.75 | 2815 | 2813 | 0.24 |

**Table 5-10. Thermal properties of sample F03A-90V-05 at ambient temperature.**

| F03A-90V-05<br>Sec low: 305.75 | Conductivity<br>(W/(m, K)) | Diffusivity<br>(mm$^2$/s) | Heat capacity<br>(MJ/(m$^3$, K)) |
|---|---|---|---|
| | 20 °C | | |
| Mean value | 2.60 | 1.17 | 2.22 |
| Standard deviation | 0.003 | 0.002 | 0.005 |

### *Sample F03A-90V-06*

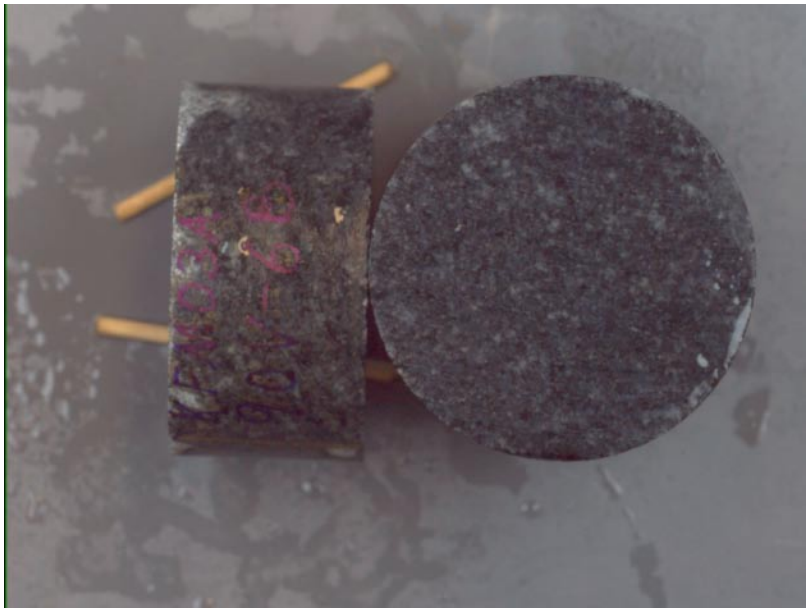

***Figure 5-6.*** *Specimens F03A-90V-06.*

**Table 5-11. Porosity, wet and dry density of specimens F03A-90V-06, average values.**

| Sample | Density, wet (kg/m$^3$) | Density, dry (kg/m$^3$) | Porosity (%) |
|---|---|---|---|
| F03A-90V-06 | | | |
| Sec low: 305.82 | 2805 | 2803 | 0.29 |

**Table 5-12. Thermal properties of sample F03A-90V-06 at ambient temperature.**

| F03A-90V-06<br>Sec low: 305.82 | Conductivity<br>(W/(m, K)) | Diffusivity<br>(mm$^2$/s) | Heat capacity<br>(MJ/(m$^3$, K)) |
|---|---|---|---|
| | | 20 °C | |
| Mean value | 2.47 | 1.14 | 2.17 |
| Standard deviation | 0.002 | 0.003 | 0.004 |

### *Sample F03A-90V-07*


***Figure 5-7.*** *Specimens F03A-90V-07.*

**Table 5-13. Porosity, wet and dry density of specimens F03A-90V-07, average values.**

| Sample | Density, wet (kg/m³) | Density, dry (kg/m³) | Porosity (%) |
|---|---|---|---|
| F03A-90V-07 | | | |
| Sec low: 527.3 | 2655 | 2649 | 0.51 |

**Table 5-14. Thermal properties of sample F03A-90V-07 at different temperatures.**

| F03A-90V-07<br>Sec low: 527.3 | Conductivity<br>(W/(m, K)) | Diffusivity<br>(mm²/s) | Heat capacity<br>(MJ/(m³, K)) |
|---|---|---|---|
| | 20 °C | | |
| Mean value | 3.42 | 1.50 | 2.27 |
| Standard deviation | 0.007 | 0.003 | 0.007 |
| | 50 °C | | |
| Mean value | 3.30 | 1.34 | 2.47 |
| Standard deviation | 0.001 | 0.009 | 0.016 |
| | 80 °C | | |
| Mean value | 3.28 | 1.22 | 2.69 |
| Standard deviation | 0.007 | 0.004 | 0.012 |

### *Sample F03A-90V-08*

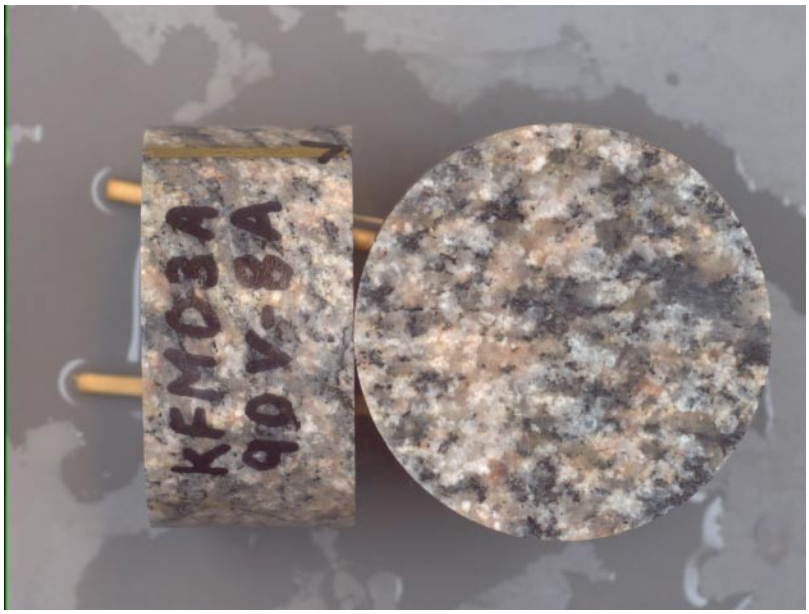


***Figure 5-8.*** *Specimens F03A-90V-08.*

**Table 5-15. Porosity, wet and dry density of specimens F03A-90V-08, average values.**

| Sample | Density, wet (kg/m³) | Density, dry (kg/m³) | Porosity (%) |
|---|---|---|---|
| F03A-90V-08 | | | |
| Sec low: 527.36 | 2650 | 2646 | 0.44 |

**Table 5-16. Thermal properties of sample F03A-90V-08 at different temperatures.**

| F03A-90V-08<br>Sec low: 527.36 | Conductivity<br>(W/(m, K)) | Diffusivity<br>(mm²/s) | Heat capacity<br>(MJ/(m³, K)) |
|---|---|---|---|
| | 20 °C | | |
| Mean value | 3.61 | 1.82 | 1.99 |
| Standard deviation | 0.015 | 0.013 | 0.007 |
| | 50 °C | | |
| Mean value | 3.54 | 1.58 | 2.24 |
| Standard deviation | 0.004 | 0.005 | 0.006 |
| | 80 °C | | |
| Mean value | 3.37 | 1.45 | 2.32 |
| Standard deviation | 0.006 | 0.009 | 0.011 |

### *Sample F03A-90V-09*


***Figure 5-9.*** *Specimens F03A-90V-09.*

**Table 5-17. Porosity, wet and dry density of specimens F03A-90V-09, average values.**

| Sample | Density, wet (kg/m³) | Density, dry (kg/m³) | Porosity (%) |
|---|---|---|---|
| F03A-90V-09 | | | |
| Sec low: 527.42 | 2646 | 2641 | 0.44 |

**Table 5-18. Thermal properties of sample F03A-90V-09 at different temperatures.**

| F03A-90V-09<br>Sec low: 527.42 | Conductivity<br>(W/(m, K)) | Diffusivity<br>(mm²/s) | Heat capacity<br>(MJ/(m³, K)) |
|---|---|---|---|
| | 20 °C | | |
| Mean value | 3.83 | 1.74 | 2.20 |
| Standard deviation | 0.008 | 0.005 | 0.007 |
| | 50 °C | | |
| Mean value | 3.75 | 1.53 | 2.46 |
| Standard deviation | 0.004 | 0.031 | 0.053 |
| | 80 °C | | |
| Mean value | 3.61 | 1.39 | 2.59 |
| Standard deviation | 0.009 | 0.008 | 0.017 |

### *Sample F03A-90V-13*

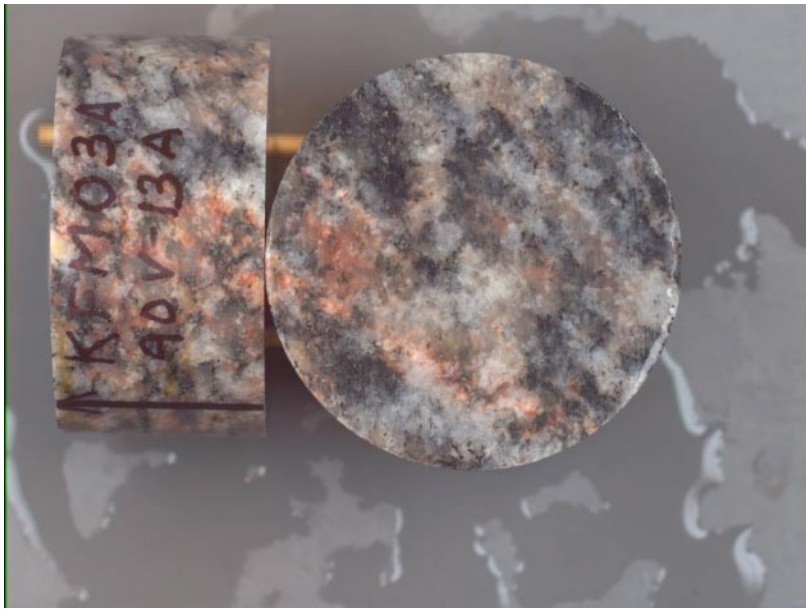


***Figure 5-10.*** *Specimens F03A-90V-13.*

**Table 5-19. Porosity, wet and dry density of specimens F03A-90V-13, average values.**

| Sample | Density, wet (kg/m$^3$) | Density, dry (kg/m$^3$) | Porosity (%) |
|---|---|---|---|
| F03A-90V-13 | | | |
| Sec low: 683.77 | 2654 | 2651 | 0.30 |

**Table 5-20. Thermal properties of sample F03A-90V-13 at ambient temperature.**

| F03A-90V-13<br>Sec low: 683.77 | Conductivity<br>(W/(m, K)) | Diffusivity<br>(mm$^2$/s) | Heat capacity<br>(MJ/(m$^3$, K)) |
|---|---|---|---|
| | 20 °C | | |
| Mean value | 3.52 | 1.64 | 2.15 |
| Standard deviation | 0.002 | 0.007 | 0.009 |

### *Sample F03A-90V-14*

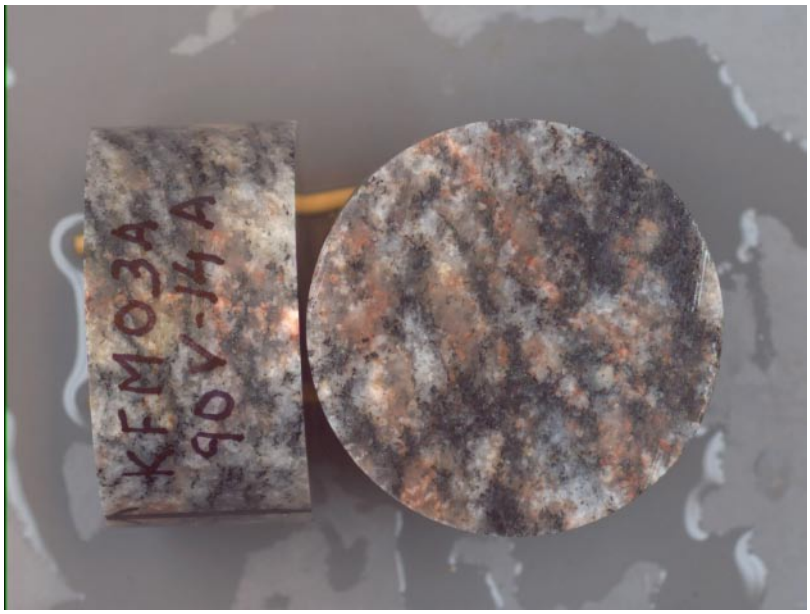


***Figure 5-11.*** *Specimens F03A-90V-14.*

**Table 5-21. Porosity, wet and dry density of specimens F03A-90V-14, average values.**

| Sample | Density, wet (kg/m³) | Density, dry (kg/m³) | Porosity (%) |
|---|---|---|---|
| F03A-90V-14 | | | |
| Sec low: 683.84 | 2654 | 2651 | 0.30 |

**Table 5-22. Thermal properties of sample F03A-90V-14 at ambient temperature.**

| F03A-90V-14<br>Sec low: 683.84 | Conductivity<br>(W/(m, K)) | Diffusivity<br>(mm²/s) | Heat capacity<br>(MJ/(m³, K)) |
|---|---|---|---|
| | 20 °C | | |
| Mean value | 3.71 | 1.80 | 2.07 |
| Standard deviation | 0.003 | 0.011 | 0.012 |

### *Sample F03A-90V-15*


***Figure 5-12.*** *Specimens F03A-90V-15.*

**Table 5-23. Porosity, wet and dry density of specimens F03A-90V-15, average values.**

| Sample | Density, wet (kg/m³) | Density, dry (kg/m³) | Porosity (%) |
|---|---|---|---|
| F03A-90V-15 | | | |
| Sec low: 683.9 | 2652 | 2649 | 0.37 |

**Table 5-24. Thermal properties of sample F03A-90V-15 at ambient temperature.**

| F03A-90V-15<br>Sec low: 683.9 | Conductivity<br>(W/(m, K)) | Diffusivity<br>(mm²/s) | Heat capacity<br>(MJ/(m³, K)) |
|---|---|---|---|
| | 20 °C | | |
| Mean value | 3.79 | 1.81 | 2.10 |
| Standard deviation | 0.009 | 0.006 | 0.006 |

### 5.1.2 Results for the entire test series

Table 5-25 - Table 5-27 show the mean value of five repeated measurements of the thermal properties. Standard deviation at different temperature levels is displayed in Table 5-28 - Table 5-30.

Thermal conductivity and thermal diffusivity of specimens at different depth at 20 °C were in the range of 2.46-3.83 W/(m, K) and 1.14-1.82 $mm^2/s$ respectively. At 50 °C, thermal conductivity and thermal diffusivity of specimens at different depths were in the range of 3.30-3.75 W/(m, K) and 1.34-1.58 $mm^2/s$ respectively and finally at 80 °C, thermal conductivity and thermal diffusivity of specimens were in the range of 3.28-3.61 W/(m, K) and 1.22-1.45 $mm^2/s$ respectively.

**Table 5-25. Mean value of thermal properties of samples at 20 °C.**

| Sample identification | Conductivity (W/(m, K)) | Diffusivity ($mm^2/s$) | Heat capacity ($MJ/(m^3, K)$) |
|---|---|---|---|
| F03A-90V-01 | 2.64 | 1.29 | 2.05 |
| F03A-90V-02 | 2.80 | 1.24 | 2.26 |
| F03A-90V-03 | 2.81 | 1.18 | 2.39 |
| **Mean value, level 260** | **2.75** | **1.23** | **2.23** |
| F03A-90V-04 | 2.46 | 1.16 | 2.13 |
| F03A-90V-05 | 2.60 | 1.17 | 2.22 |
| F03A-90V-06 | 2.47 | 1.14 | 2.17 |
| **Mean value, level 305** | **2.51** | **1.16** | **2.17** |
| F03A-90V-07 | 3.42 | 1.50 | 2.27 |
| F03A-90V-08 | 3.61 | 1.82 | 1.99 |
| F03A-90V-09 | 3.83 | 1.74 | 2.20 |
| **Mean value, level 525** | **3.62** | **1.69** | **2.15** |
| F03A-90V-13 | 3.52 | 1.64 | 2.15 |
| F03A-90V-14 | 3.71 | 1.80 | 2.07 |
| F03A-90V-15 | 3.79 | 1.81 | 2.10 |
| **Mean value, level 685** | **3.67** | **1.75** | **2.11** |

**Table 5-26. Mean value of thermal properties of samples at 50 °C.**

| Sample identification | Conductivity (W/(m, K)) | Diffusivity ($mm^2/s$) | Heat capacity ($MJ/(m^3, K)$) |
|---|---|---|---|
| F03A-90V-07 | 3.30 | 1.34 | 2.47 |
| F03A-90V-08 | 3.54 | 1.58 | 2.24 |
| F03A-90V-09 | 3.75 | 1.53 | 2.46 |
| **Mean value, level 525** | **3.53** | **1.48** | **2.39** |

**Table 5-27. Mean value of thermal properties of samples at 80 °C.**

| Sample identification | Conductivity (W/(m, K)) | Diffusivity ($mm^2/s$) | Heat capacity ($MJ/(m^3, K)$) |
|---|---|---|---|
| F03A-90V-07 | 3.28 | 1.22 | 2.69 |
| F03A-90V-08 | 3.37 | 1.45 | 2.32 |
| F03A-90V-09 | 3.61 | 1.39 | 2.59 |
| **Mean value, level 525** | **3.42** | **1.36** | **2.53** |

**Table 5-28. Standard deviation of measured values at 20 °C.**

| Sample identification | Conductivity (W/(m, K)) | Diffusivity ($mm^2/s$) | Heat capacity ($MJ/(m^3, K)$) |
|---|---|---|---|
| F03A-90V-01 | 0.002 | 0.003 | 0.005 |
| F03A-90V-02 | 0.004 | 0.005 | 0.011 |
| F03A-90V-03 | 0.002 | 0.001 | 0.003 |
| F03A-90V-04 | 0.002 | 0.003 | 0.005 |
| F03A-90V-05 | 0.003 | 0.002 | 0.005 |
| F03A-90V-06 | 0.002 | 0.003 | 0.004 |
| F03A-90V-07 | 0.007 | 0.003 | 0.007 |
| F03A-90V-08 | 0.015 | 0.013 | 0.007 |
| F03A-90V-09 | 0.008 | 0.005 | 0.007 |
| F03A-90V-13 | 0.002 | 0.007 | 0.009 |
| F03A-90V-14 | 0.003 | 0.011 | 0.012 |
| F03A-90V-15 | 0.009 | 0.006 | 0.006 |

**Table 5-29. Standard deviation of measured values at 50 °C.**

| Sample identification | Conductivity (W/(m, K)) | Diffusivity ($mm^2/s$) | Heat capacity ($MJ/(m^3, K)$) |
|---|---|---|---|
| F03A-90V-07 | 0.001 | 0.009 | 0.016 |
| F03A-90V-08 | 0.004 | 0.005 | 0.006 |
| F03A-90V-09 | 0.004 | 0.031 | 0.053 |

**Table 5-30. Standard deviation of measured values at 80 °C.**

| Sample identification | Conductivity (W/(m, K)) | Diffusivity ($mm^2/s$) | Heat capacity ($MJ/(m^3, K)$) |
|---|---|---|---|
| F03A-90V-07 | 0.007 | 0.004 | 0.012 |
| F03A-90V-08 | 0.006 | 0.009 | 0.011 |
| F03A-90V-09 | 0.009 | 0.008 | 0.017 |

### 5.1.3 Graphical presentation of results

Variation of the thermal conductivity and heat capacity in relation to depth of the sampling at different temperatures are shown in Figure 5-13 - Figure 5-17.

Maximum variation of thermal conductivity in the temperature range 20 ºC to 80 ºC was 7 % for sample F03A-90V-8 and maximum variation of heat capacity in the same temperature range was about 16 % for sample F03A-90V-07.

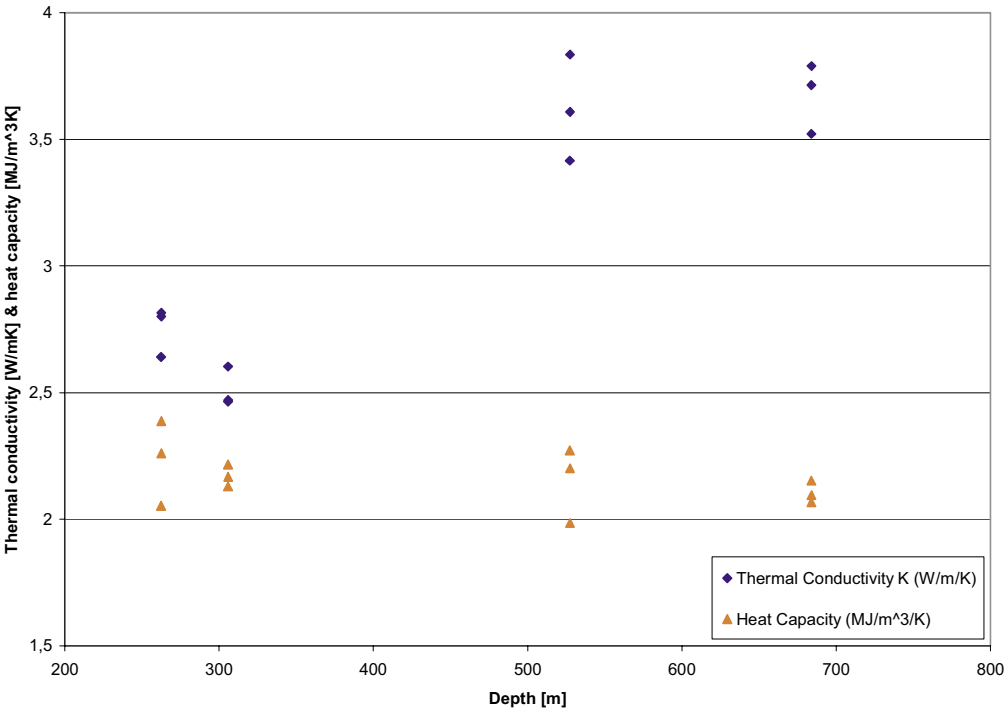


***Figure 5-13.*** *Thermal conductivity and heat capacity at different depths at 20 °C.*

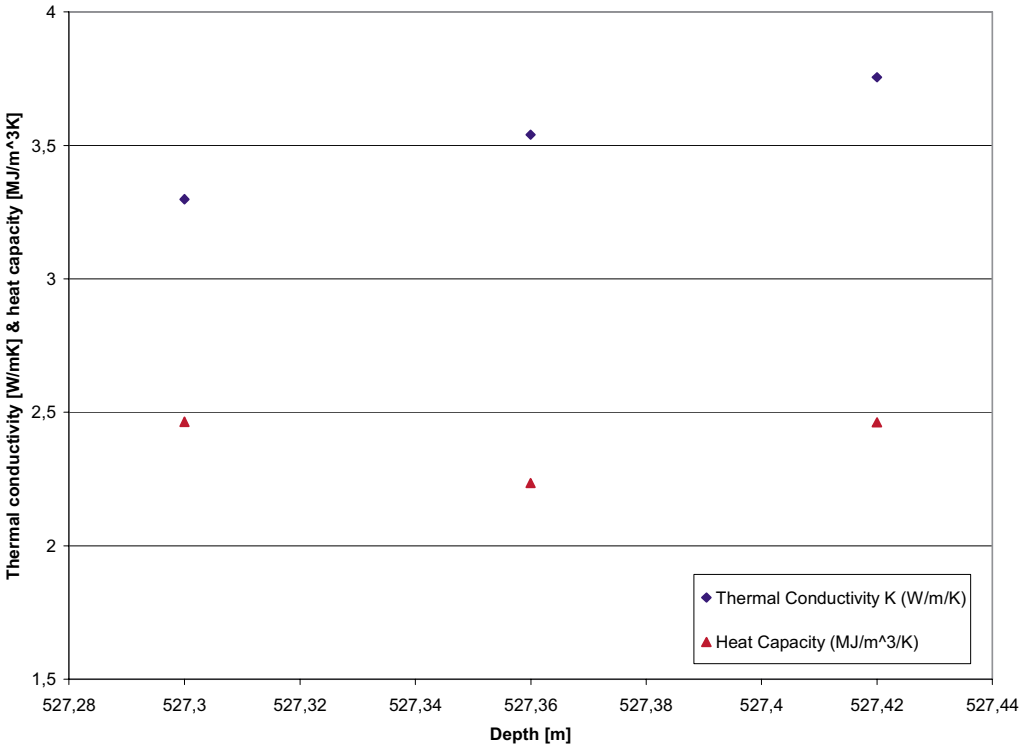


***Figure 5-14.*** *Thermal conductivity and heat capacity at different depths at 50 °C.*

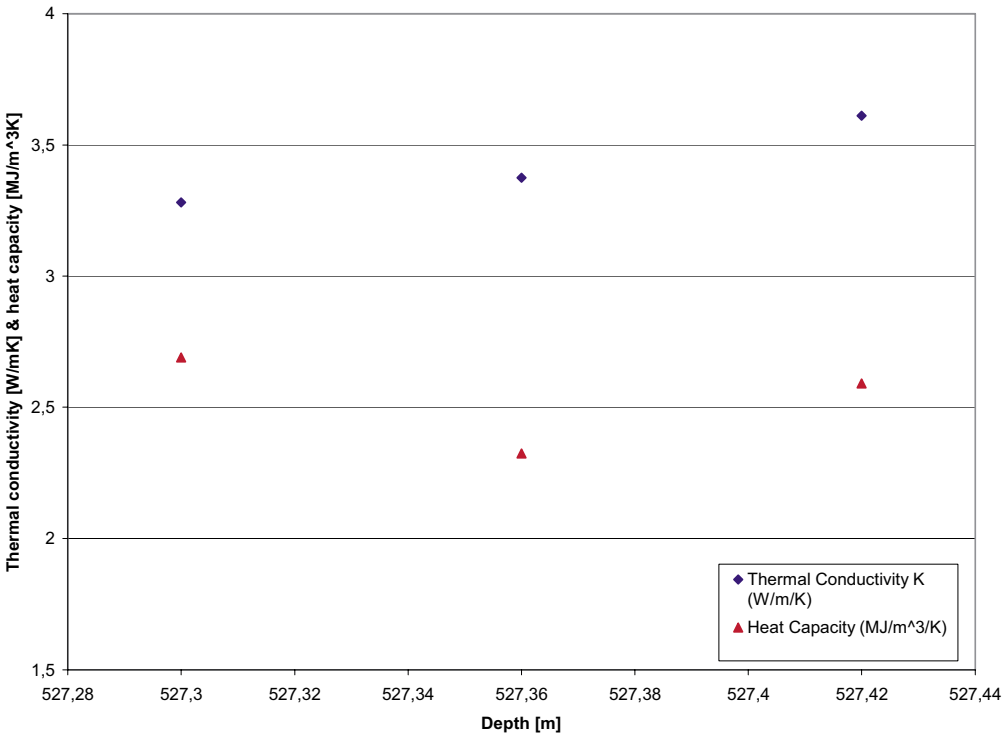


***Figure 5-15.*** *Thermal conductivity and heat capacity at different depths at 80 °C.*

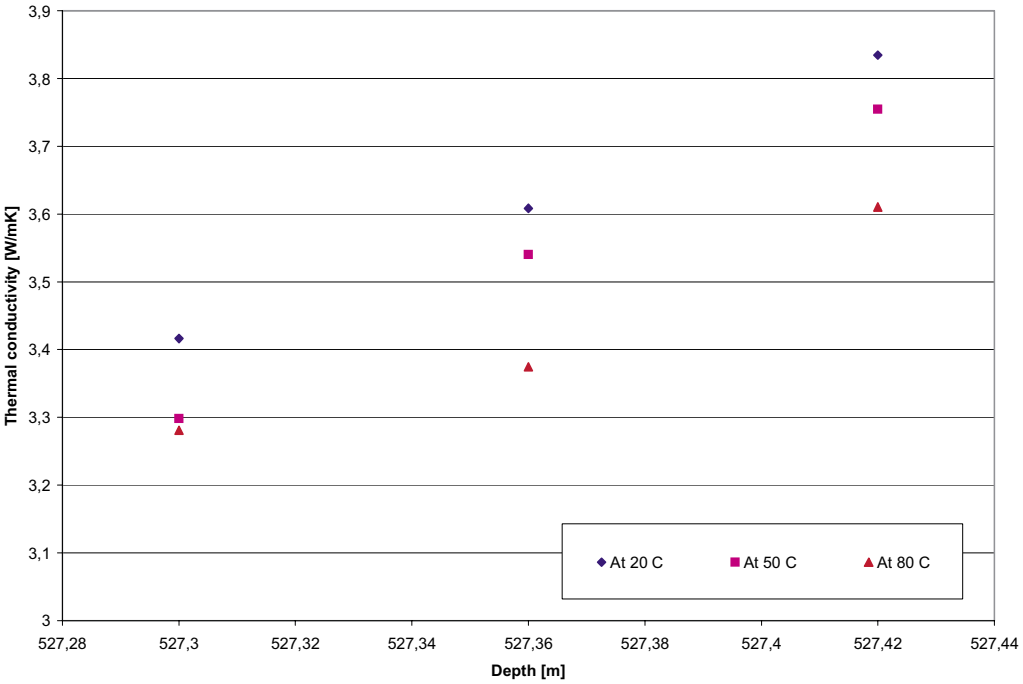


***Figure 5-16.*** *Thermal conductivity at different depth and at different temperatures.*

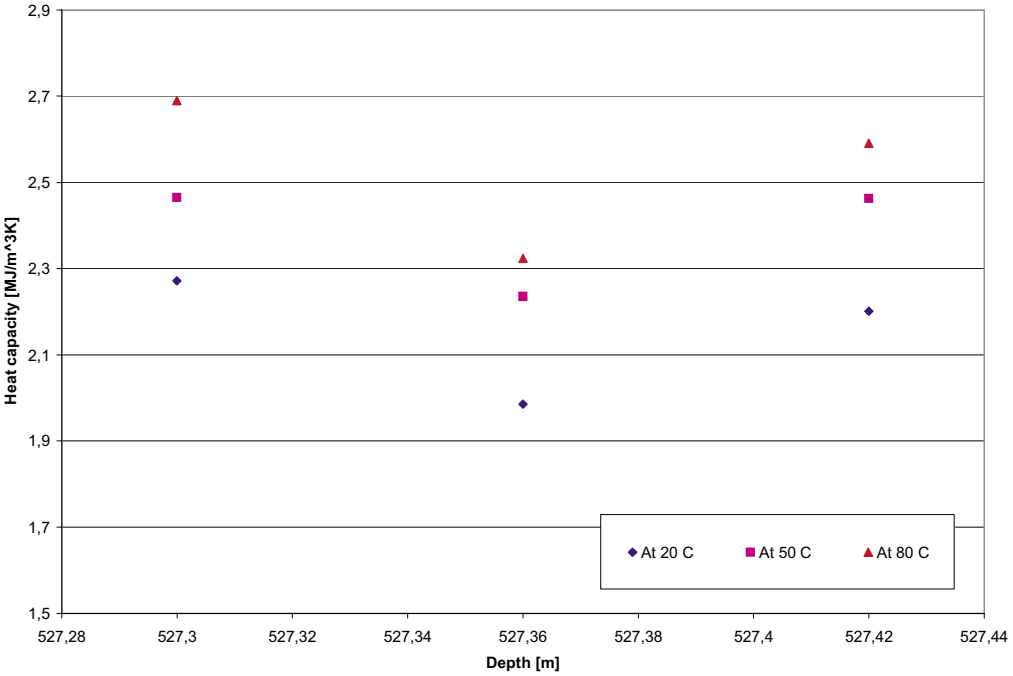


***Figure 5-17.*** *Heat capacity at different depth and at different temperatures.*

## 5.2 Modal analysis

Modal analyses, based on point counting using a polarising microscope were performed on 6 specimens that were sampled on the same level as the specimens for thermal properties (see Sec up in Table 5-31 and Sec low in Table 4-1). The modal analyses were done in order to calculate the thermal properties based on the specimen's mineralogical composition.

**Table 5-31. Mineralogical composition (in vol. %) of the six investigated specimens from KFM03A 500 points are counted on each specimen.**

| Identification | Sampling depth (Sec up) | Qtz | Kfs | Pl | Bt | Ch | Op | Amp | As |
|---|---|---|---|---|---|---|---|---|---|
| KFM03A-200-1 | 262.56 | 22 | 38 | 11 | 12 | - | - | 9 | 8 |
| KFM03A-200-2 | 305.87 | 19 | 41 | 5 | 13 | - | - | 19 | 4 |
| KFM03A-200-3 | 527.51 | 42 | 29 | 20 | 6 | - | - | - | 2 |
| KFM03A-200-4 | 527.70 | 42 | 28 | 24 | 6 | - | - | - | 1 |
| KFM03A-200-5 | 684.21 | 33 | 28 | 32 | 7 | - | - | - | 0 |
| KFM03A-200-6 | 685.13 | 36 | 26 | 31 | 6 | - | - | - | 1 |

The mineral mode is based on point counting using a polarising microscope.

Qtz= Quartz, Kfs= K-feldspar, Pl= Plagioclase, Bt= Biotite, Ch=chlorite, Op=opaque minerals, Amp=amphibole, As= Accessory minerals.

## 5.3 Nonconformities

There were no deviations from the plans.

# 6 References


/1/ **Gustafsson, S E, 1991.** “Transient plane source techniques for thermal conductivity and thermal diffusivity measurements of solid materials”. Rev. Sci. Instrum. 62 (3), March 1991, American Institute of Physics

/2/ **Instruction Manual Hot Disc Thermal Constants Analyser Windows 95 Version 5.0, 2001.**

/3/ **ISRM Commission on Testing Methods, ISRM, 1979.**

# Appendix A

**Calibration protocol for Hot Disk Bridge System**

| | | |
|---|---|---|
| Electronics: | Keithley 2400 | Serial No. 0925167 |
| | Keithley 2000 | Serial No. 0921454 |
| Hot Disk Bridge: | Serial No. 2003-0004 | |
| Computation Device: | Serial No. 2003-0003, ver 1.4.2 | |
| Computer: | Hot Disk computer | Serial No. 2003-0003 |
| Test sample: | SIS2343, mild steel | Serial No. 3.52 |
| Sensor for testing: | C5501 | |

Test measurement: 10 repeated measurements on the test sample at room temperature.

Conditions: Power 1 W, Measurement time 10 s

Results

| | | |
|---|---|---|
| Thermal Conductivity: | 13.48 W/(m, K) | ±0.04 % |
| Thermal Diffusivity: | 3.528 $mm^2/s$ | ±0.16 % |
| Heat Capacity: | 3.955 $MJ/(m^3, K)$ | ±0.15 % |

This instrument has proved to behave according to specifications described in BRk-QB-M26-02.

Borås 07/01 2004

Bijan Adl-Zarrabi

# Appendix B

**Table B-1. Thermal properties of samples at 20 °C.**

| Measurement number | Conductivity (W/(m, K)) | Diffusivity ($mm^2/s$) | Heat capacity ($MJ/(m^3, K)$) |
|---|---|---|---|
| F03A-90V-01 | | | |
| 1 | 2.64 | 1.28 | 2.05 |
| 2 | 2.64 | 1.28 | 2.06 |
| 3 | 2.64 | 1.29 | 2.05 |
| 4 | 2.64 | 1.29 | 2.05 |
| 5 | 2.64 | 1.28 | 2.06 |
| F03A-90V-02 | | | |
| 1 | 2.80 | 1.24 | 2.26 |
| 2 | 2.80 | 1.24 | 2.27 |
| 3 | 2.80 | 1.23 | 2.27 |
| 4 | 2.80 | 1.24 | 2.26 |
| 5 | 2.79 | 1.25 | 2.24 |
| F03A-90V-03 | | | |
| 1 | 2.81 | 1.18 | 2.39 |
| 2 | 2.82 | 1.18 | 2.39 |
| 3 | 2.81 | 1.18 | 2.39 |
| 4 | 2.81 | 1.18 | 2.38 |
| 5 | 2.81 | 1.18 | 2.39 |
| F03A-90V-04 | | | |
| 1 | 2.46 | 1.16 | 2.12 |
| 2 | 2.46 | 1.16 | 2.13 |
| 3 | 2.47 | 1.16 | 2.13 |
| 4 | 2.47 | 1.16 | 2.13 |
| 5 | 2.47 | 1.15 | 2.14 |
| F03A-90V-05 | | | |
| 1 | 2.60 | 1.18 | 2.21 |
| 2 | 2.61 | 1.18 | 2.22 |
| 3 | 2.61 | 1.17 | 2.22 |
| 4 | 2.60 | 1.17 | 2.22 |
| 5 | 2.60 | 1.17 | 2.22 |
| F03A-90V-06 | | | |
| 1 | 2.47 | 1.14 | 2.16 |
| 2 | 2.47 | 1.14 | 2.17 |
| 3 | 2.47 | 1.14 | 2.17 |
| 4 | 2.47 | 1.14 | 2.17 |
| 5 | 2.47 | 1.14 | 2.17 |
| F03A-90V-07 | | | |
| 1 | 3.42 | 1.51 | 2.27 |
| 2 | 3.42 | 1.50 | 2.28 |
| 3 | 3.42 | 1.50 | 2.28 |
| 4 | 3.41 | 1.51 | 2.27 |
| 5 | 3.41 | 1.50 | 2.26 |
| F03A-90V-08 | | | |
| 1 | 3.62 | 1.83 | 1.98 |
| 2 | 3.62 | 1.82 | 1.99 |
| 3 | 3.61 | 1.83 | 1.98 |
| 4 | 3.58 | 1.79 | 2.00 |
| 5 | 3.61 | 1.82 | 1.98 |

| Measurement number | Conductivity (W/(m, K)) | Diffusivity ($mm^2/s$) | Heat capacity ($MJ/(m^3, K)$) |
|---|---|---|---|
| F03A-90V-09 | | | |
| 1 | 3.85 | 1.75 | 2.20 |
| 2 | 3.83 | 1.75 | 2.20 |
| 3 | 3.84 | 1.74 | 2.21 |
| 4 | 3.83 | 1.74 | 2.20 |
| 5 | 3.83 | 1.74 | 2.19 |
| F03A-90V-13 | | | |
| 1 | 3.52 | 1.65 | 2.14 |
| 2 | 3.53 | 1.64 | 2.15 |
| 3 | 3.52 | 1.64 | 2.15 |
| 4 | 3.52 | 1.64 | 2.15 |
| 5 | 3.52 | 1.63 | 2.17 |
| F03A-90V-14 | | | |
| 1 | 3.71 | 1.80 | 2.06 |
| 2 | 3.72 | 1.79 | 2.07 |
| 3 | 3.71 | 1.78 | 2.08 |
| 4 | 3.71 | 1.79 | 2.07 |
| 5 | 3.72 | 1.81 | 2.05 |
| F03A-90V-15 | | | |
| 1 | 3.80 | 1.81 | 2.09 |
| 2 | 3.80 | 1.81 | 2.10 |
| 3 | 3.79 | 1.81 | 2.09 |
| 4 | 3.78 | 1.81 | 2.09 |
| 5 | 3.78 | 1.80 | 2.10 |

**Table B-2. Thermal properties of samples at 50 °C.**

| Measurement number | Conductivity (W/(m, K)) | Diffusivity ($mm^2/s$) | Heat capacity ($MJ/(m^3, K)$) |
|---|---|---|---|
| F03A-90V-07 | | | |
| 1 | 3.30 | 1.32 | 2.49 |
| 2 | 3.30 | 1.34 | 2.47 |
| 3 | 3.30 | 1.34 | 2.45 |
| 4 | 3.30 | 1.34 | 2.46 |
| 5 | 3.30 | 1.34 | 2.46 |
| F01A-90V-08 | | | |
| 1 | 3.54 | 1.59 | 2.23 |
| 2 | 3.54 | 1.59 | 2.23 |
| 3 | 3.54 | 1.58 | 2.24 |
| 4 | 3.54 | 1.58 | 2.24 |
| 5 | 3.54 | 1.58 | 2.24 |
| F03A-90V-09 | | | |
| 1 | 3.75 | 1.53 | 2.45 |
| 2 | 3.76 | 1.54 | 2.44 |
| 3 | 3.75 | 1.54 | 2.43 |
| 4 | 3.75 | 1.54 | 2.44 |
| 5 | 3.76 | 1.47 | 2.56 |

**Table B-3. Thermal properties of samples at 80 °C.**

| Measurement number | Conductivity (W/(m, K)) | Diffusivity ($mm^2/s$) | Heat capacity ($MJ/(m^3, K)$) |
|---|---|---|---|
| F03A-90V-07 | | | |
| 1 | 3.29 | 1.22 | 2.69 |
| 2 | 3.29 | 1.21 | 2.71 |
| 3 | 3.28 | 1.22 | 2.69 |
| 4 | 3.28 | 1.22 | 2.68 |
| 5 | 3.27 | 1.22 | 2.68 |
| F01A-90V-08 | | | |
| 1 | 3.38 | 1.46 | 2.32 |
| 2 | 3.38 | 1.46 | 2.31 |
| 3 | 3.37 | 1.46 | 2.31 |
| 4 | 3.37 | 1.45 | 2.33 |
| 5 | 3.37 | 1.44 | 2.34 |
| F03A-90V-09 | | | |
| 1 | 3.61 | 1.38 | 2.62 |
| 2 | 3.62 | 1.40 | 2.59 |
| 3 | 3.61 | 1.39 | 2.59 |
| 4 | 3.60 | 1.40 | 2.58 |
| 5 | 3.60 | 1.40 | 2.57 |

# Appendix C

**Table C-1. Total time of measurement, ratio of total time and characteristic time, and number of analysed points at 20 °C.**

| Measurement number | Total time(s) | Total/Char. Time | Points |
|---|---|---|---|
| F03A-90V-01 | | | |
| 1 | 20 | 0.62 | 44- 200 |
| 2 | 20 | 0.62 | 53- 200 |
| 3 | 20 | 0.63 | 63- 200 |
| 4 | 20 | 0.63 | 59- 200 |
| 5 | 20 | 0.62 | 44- 200 |
| F03A-90V-02 | | | |
| 1 | 20 | 0.60 | 24- 200 |
| 2 | 20 | 0.60 | 23- 200 |
| 3 | 20 | 0.60 | 24- 200 |
| 4 | 20 | 0.60 | 21- 200 |
| 5 | 20 | 0.60 | 26- 200 |
| F03A-90V-03 | | | |
| 1 | 20 | 0.57 | 59- 200 |
| 2 | 20 | 0.57 | 54- 200 |
| 3 | 20 | 0.57 | 60- 200 |
| 4 | 20 | 0.57 | 55- 200 |
| 5 | 20 | 0.57 | 54- 200 |
| F03A-90V-04 | | | |
| 1 | 20 | 0.56 | 63- 200 |
| 2 | 20 | 0.56 | 55- 200 |
| 3 | 20 | 0.56 | 61- 200 |
| 4 | 20 | 0.56 | 65- 200 |
| 5 | 20 | 0.56 | 65- 200 |
| F03A-90V-05 | | | |
| 1 | 20 | 0.57 | 28- 199 |
| 2 | 20 | 0.57 | 30- 200 |
| 3 | 20 | 0.57 | 29- 200 |
| 4 | 20 | 0.57 | 23- 200 |
| 5 | 20 | 0.57 | 25- 200 |
| F03A-90V-06 | | | |
| 1 | 20 | 0.55 | 22- 200 |
| 2 | 20 | 0.55 | 22- 200 |
| 3 | 20 | 0.55 | 25- 200 |
| 4 | 20 | 0.55 | 22- 200 |
| 5 | 20 | 0.55 | 21- 200 |

**Table C-1. Total time of measurement, ratio of total time and characteristic (continues) time, and number of analysed points at 20 °C.**

| Measurement number | Total time(s) | Total/Char. Time | Points |
|---|---|---|---|
| F03A-90V-07 | | | |
| 1 | 20 | 0.73 | 21- 200 |
| 2 | 20 | 0.72 | 22- 198 |
| 3 | 20 | 0.73 | 19- 200 |
| 4 | 20 | 0.73 | 25- 200 |
| 5 | 20 | 0.73 | 24- 200 |
| F03A-90V-08 | | | |
| 1 | 20 | 0.89 | 56- 200 |
| 2 | 20 | 0.88 | 56- 200 |
| 3 | 20 | 0.89 | 60- 200 |
| 4 | 20 | 0.87 | 47- 200 |
| 5 | 20 | 0.88 | 49- 200 |
| F03A-90V-09 | | | |
| 1 | 20 | 0.85 | 28- 200 |
| 2 | 20 | 0.85 | 31- 200 |
| 3 | 20 | 0.84 | 30- 199 |
| 4 | 20 | 0.84 | 32- 198 |
| 5 | 20 | 0.85 | 31- 200 |
| F03A-90V-13 | | | |
| 1 | 20 | 0.80 | 41- 200 |
| 2 | 20 | 0.79 | 36- 200 |
| 3 | 20 | 0.79 | 39- 200 |
| 4 | 20 | 0.79 | 35- 200 |
| 5 | 20 | 0.79 | 42- 200 |
| F03A-90V-14 | | | |
| 1 | 20 | 0.87 | 18- 200 |
| 2 | 20 | 0.87 | 18- 200 |
| 3 | 20 | 0.87 | 16- 200 |
| 4 | 20 | 0.87 | 16- 200 |
| 5 | 20 | 0.88 | 23- 200 |
| F03A-90V-15 | | | |
| 1 | 20 | 0.85 | 28- 193 |
| 2 | 20 | 0.88 | 31- 200 |
| 3 | 20 | 0.84 | 24- 191 |
| 4 | 20 | 0.86 | 27- 196 |
| 5 | 20 | 0.85 | 25- 195 |

**Table C-2. Total time of measurement, ratio of total time and characteristic time, and number of analysed points at 50 °C.**

| Measurement number | Total time(s) | Total/Char. Time | Points |
|---|---|---|---|
| F03A-90V-07 | | | |
| 1 | 20 | 0.64 | 24- 200 |
| 2 | 20 | 0.65 | 23- 200 |
| 3 | 20 | 0.65 | 26- 200 |
| 4 | 20 | 0.65 | 31- 200 |
| 5 | 20 | 0.65 | 23- 199 |
| F01A-90V-08 | | | |
| 1 | 20 | 0.77 | 20- 200 |
| 2 | 20 | 0.77 | 20- 200 |
| 3 | 20 | 0.77 | 20- 200 |
| 4 | 20 | 0.77 | 20- 200 |
| 5 | 20 | 0.77 | 24- 200 |
| F03A-90V-09 | | | |
| 1 | 20 | 0.74 | 24- 200 |
| 2 | 20 | 0.75 | 32- 200 |
| 3 | 20 | 0.73 | 22- 196 |
| 4 | 20 | 0.75 | 26- 200 |
| 5 | 20 | 0.70 | 53- 195 |

**Table C-3. Total time of measurement, ratio of total time and characteristic time, and number of analysed points at 80 °C.**

| Measurement number | Total time(s) | Total/Char. Time | Points |
|---|---|---|---|
| F03A-90V-07 | | | |
| 1 | 20 | 0.59 | 20- 200 |
| 2 | 20 | 0.59 | 20- 200 |
| 3 | 20 | 0.56 | 21- 190 |
| 4 | 20 | 0.59 | 20- 200 |
| 5 | 20 | 0.59 | 20- 200 |
| F01A-90V-08 | | | |
| 1 | 20 | 0.71 | 52- 200 |
| 2 | 20 | 0.70 | 42- 197 |
| 3 | 20 | 0.69 | 43- 195 |
| 4 | 20 | 0.69 | 39- 196 |
| 5 | 20 | 0.70 | 48- 199 |
| F03A-90V-09 | | | |
| 1 | 20 | 0.67 | 26- 200 |
| 2 | 20 | 0.68 | 29- 200 |
| 3 | 20 | 0.68 | 24- 200 |
| 4 | 20 | 0.68 | 22- 200 |
| 5 | 20 | 0.68 | 21- 200 |