P-04-267

Oskarshamn site investigation

Drill hole KLX04A

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

October 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

SKB

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Keywords: 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 KLX04A, Laxemar, were measured at ambient and elevated temperature. The rock type of the samples is mapped as Ävrö granite. 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 and thermal diffusivity of specimens at different depth at 20°C were in the range of 2.47–3.43 W/(m, K) and 1.05–1.67 mm^2/s respectively. At 80°C, thermal conductivity and thermal diffusivity of specimens were in the range of 2.42–2.58 W/(m, K) and 0.91–1.11 mm^2/s respectively.

Sammanfattning

Termiska egenskaper hos femton provkroppar från borrhål KLX04A, Laxemar, bestämdes vid rumstemperatur och vid högre temperatur. Bergarten är av typen Ävrö granit. Det mineralogiska innehållet bestämdes med hjälp av modalanalys.

TPS metoden, ”Transient Plane Source”, användes för bestämning av de termiska egenskaperna. Gustafsson 1991 /1/.

Generellt var inverkan av temperaturen större på den termiska diffusiviteten än på den termiska konduktiviteten. Den termiska konduktiviteten och den termiska diffusiviteten hos provkropparna vid 20°C och vid olika djup var i intervallet 2.47–3.43 W/(m, K) respektive 1,05–1,67 mm^2/s. Vid 80°C var den termiska konduktiviteten och den termiska diffusiviteten hos provkropparna i intervallet 2,42–2,58 W/(m, K) respektive 0,91–1,11 mm^2/s.

Contents

1 Introduction

The objective of this investigation was to measure thermal properties of borehole KLX04A, Laxemar, 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 properties. 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 PS 400–04-073 (SKB internal controlling document) and is controlled by SP-QD 13.1 (SP quality document).

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.

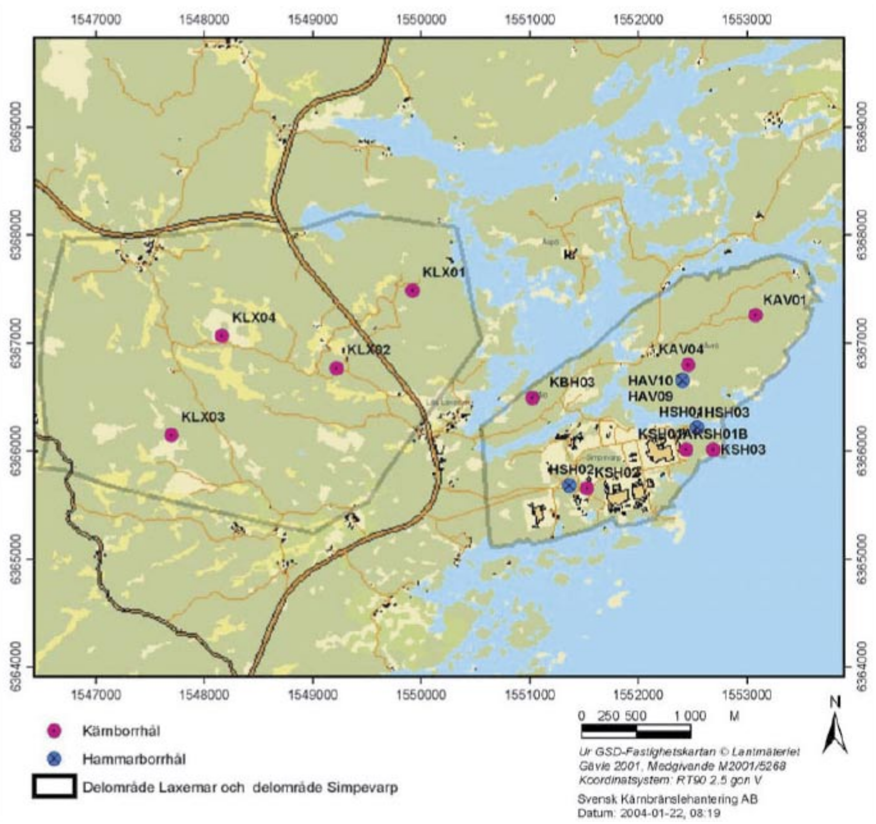

Figure 1-1. Location of the drill hole KLX04A at the Laxemar site.

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 August 2004. The testing was performed during September 2004.

Determination of thermal properties was made in accordance to SKB's method description SKB MD 191.001, version 2.0 (SKB internal controlling document) at SP Fire Technology. Density was determined in accordance to SKB MD 160.002, version 2.0 (SKB internal controlling document) at SP Building Technology and Mechanics.

Modal analyses are 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 Simpevarp.

The samples are from the borehole KLX04A in Laxemar. The specimens were sampled on three levels in the drill hole: 310 m, 565 m, and 745 m. The investigated rock type is mapped as Ävrö granite.

3 Equipment

Technical devices for determination of thermal properties used 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.

Specimen mounting is shown in Figure 3-2.

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

- Leitz Orthoplan optical microscope (inv nr 100276).

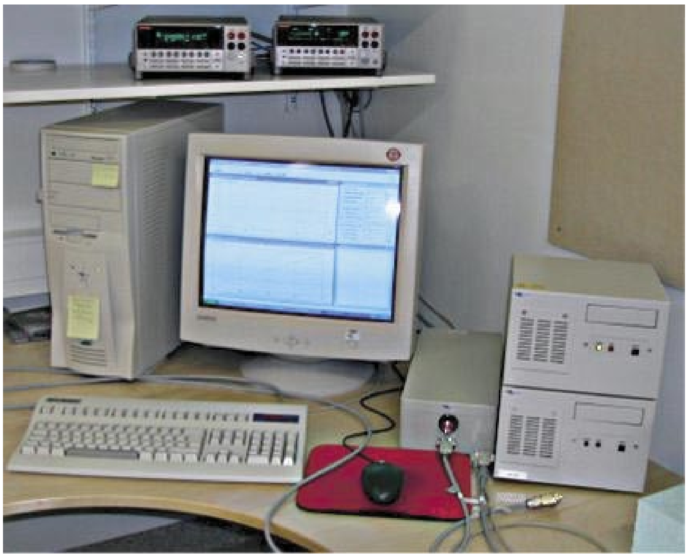

Figure 3-1. *TPS-apparatus with source meter, multi-meter, bridge, and computer.*

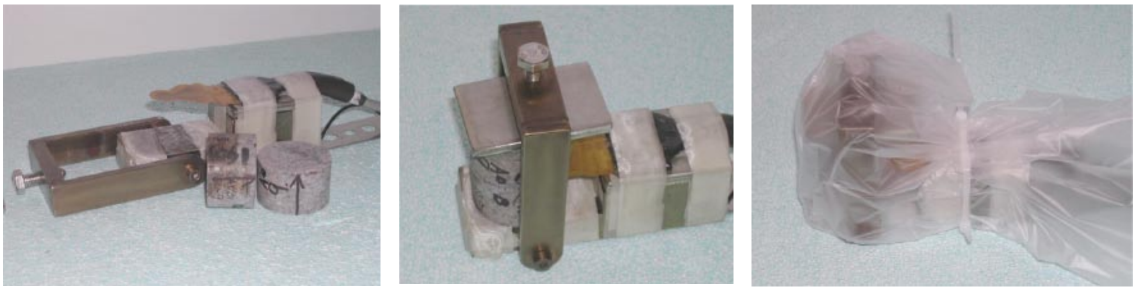

Figure 3-2. *Specimens prior to mounting (left), mounted in stainless sample holder (middle), and sample holder with mounted specimens wrapped in plastic (right).*

4 Execution

Determination of thermal properties was made in accordance to SKB's method description SKB MD 191.001, version 2.0 (SKB internal controlling document) and Hot Disc Instruction Manual /2/ at SP Fire Technology.

Density was determined in accordance to SKB MD 160.002, version 2.0 (SKB internal controlling document) and ISRM /3/. Modal analysis was determined in according to SKB MD 160.001 (SKB internal controlling document) at SP Building Technology and Mechanics.

4.1 Description of the samples

Fifteen pairs of cores were sampled from three levels of drill hole KLX04A, Simpevarp, Sweden. The first level was between 308 m and 312 m, the second level was between 562 m and 567 m, and the third level between 739 m and 746 m. The thirty specimens with a thickness of 25 mm each were sampled from the samples at SP; see Figure 3-2. The diameter of the specimens was about 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 KLX04A and in the SICADA database at SKB.

Shortened sample identification X04A-90V has been used through out the report.

Table 4-1. Rock type and identification marks (Rock-type classification according to bore map).

Identification	Rock type	Sampling depth (Sec low)
KLX04A-90V-1	Ävrö granite	312.40
KLX04A-90V-2	Ävrö granite	312.46
KLX04A-90V-3	Ävrö granite	312.52
KLX04A-90V-4	Ävrö granite	308.20
KLX04A-90V-5	Ävrö granite	308.26
KLX04A-90V-7	Ävrö granite	562.14
KLX04A-90V-8	Ävrö granite	562.20
KLX04A-90V-10	Ävrö granite	567.25
KLX04A-90V-11	Ävrö granite	567.31
KLX04A-90V-12	Ävrö granite	567.37
KLX04A-90V-13	Ävrö granite	739.54
KLX04A-90V-14	Ävrö granite	739.60
KLX04A-90V-15	Ävrö granite	739.66
KLX04A-90V-16	Ävrö granite	746.45
KLX04A-90V-17	Ävrö granite	746.51

4.2 Test Procedure

4.2.1 Thermal properties

The following steps were performed:

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

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. These stored files were sent to SKB catalogue at 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 September–October 2004.

Dry weight was measured after the specimens had been dried to constant mass according to ISMR /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 SGU.

The analysis was performed on 6 specimens that were sampled on the same level as the specimens for thermal properties (see Sec low in Table 4-1). 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 (FN 428) 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 is 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 X04A-90V-01

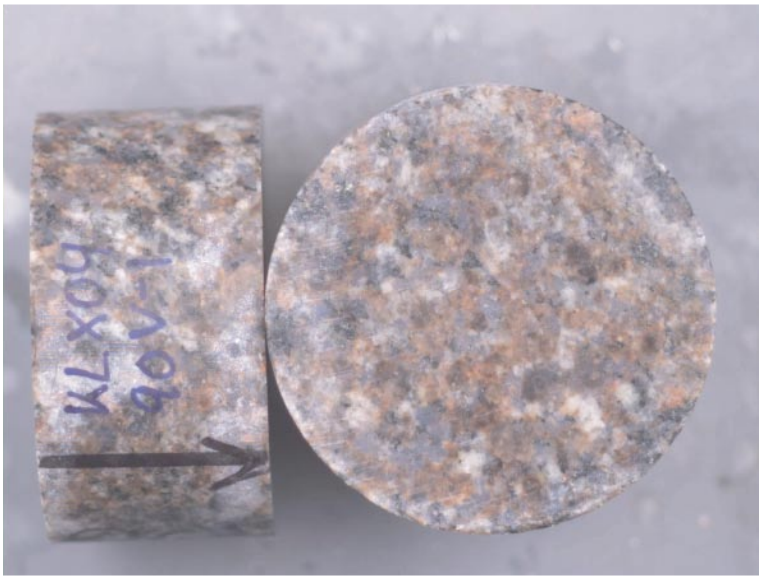

Figure 5-1. *Specimens X04A-90V-01.*

Table 5-1. Porosity, wet and dry density of specimens X04A-90V-01, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X04A-90V-01			
Sec low: 312.4	2,647	2,641	0.6

Table 5-2. Thermal properties of sample X04A-90V-01 at ambient temperature.

X04A-90V-01 Sec low: 312.4	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³· K))
	20°C		
Mean value	3.43	1.61	2.13
Standard deviation	0.005	0.006	0.011

Sample X04A-90V-02

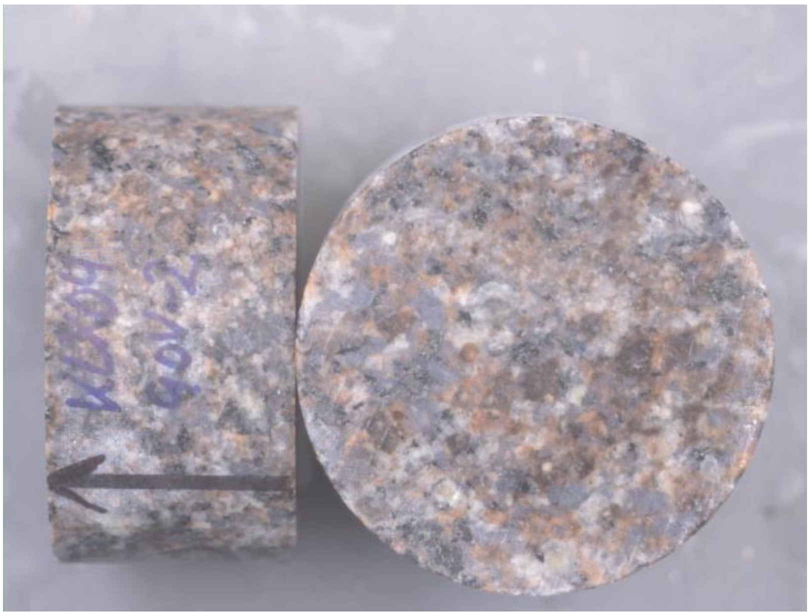

Figure 5-2. *Specimens X04A-90V-02*

Table 5-3. Porosity, wet and dry density of specimens X04A-90V-02, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X04A-90V-02	2,654	2,648	0.6
Sec low: 312.46			

Table 5-4. Thermal properties of sample X04A-90V-02 at ambient temperature.

X04A-90V-02 Sec low: 312.46	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.40	1.50	2.26
Standard deviation	0.002	0.002	0.003

Sample X04A-90V-03

Figure 5-3. *Specimens X04A-90V-03.*

Table 5-5. Porosity, wet and dry density of specimens X04A-90V-03, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X04A-90V-03 Sec low: 312.52	2,655	2,648	0.7

Table 5-6. Thermal properties of sample X04A-90V-03 at ambient temperature.

X04A-90V-03 Sec low: 312.52	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.30	1.67	1.97
Standard deviation	0.012	0.018	0.017

Sample X04A-90V-04

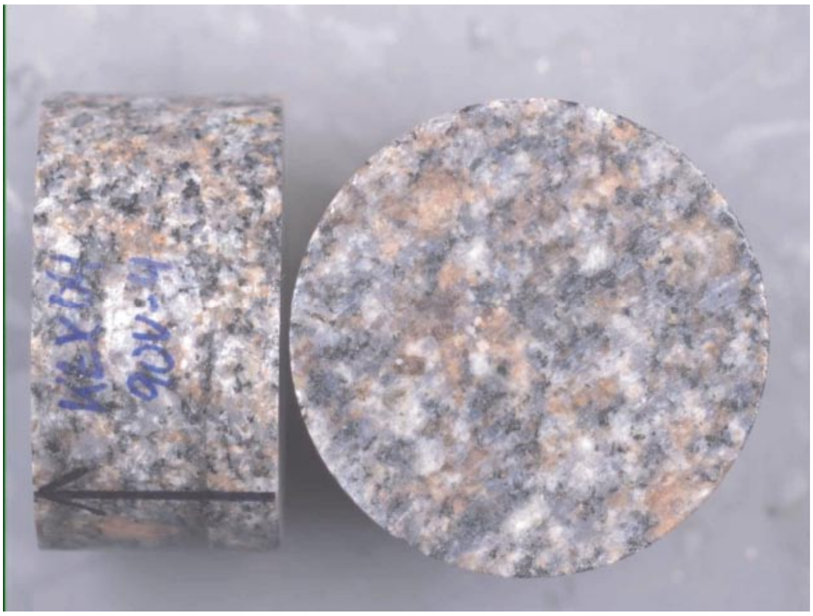

Figure 5-4. *Specimens X04A-90V-04.*

Table 5-7. Porosity, wet and dry density of specimens X04A-90V-04, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X04A-90V-04	2,670	2,664	0.6
Sec low: 308.2			

Table 5-8. Thermal properties of sample X04A-90V-04 at ambient temperature.

X04A-90V-04 Sec low: 308.2	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.18	1.38	2.30
Standard deviation	0.005	0.007	0.014

Sample X04A-90V-05

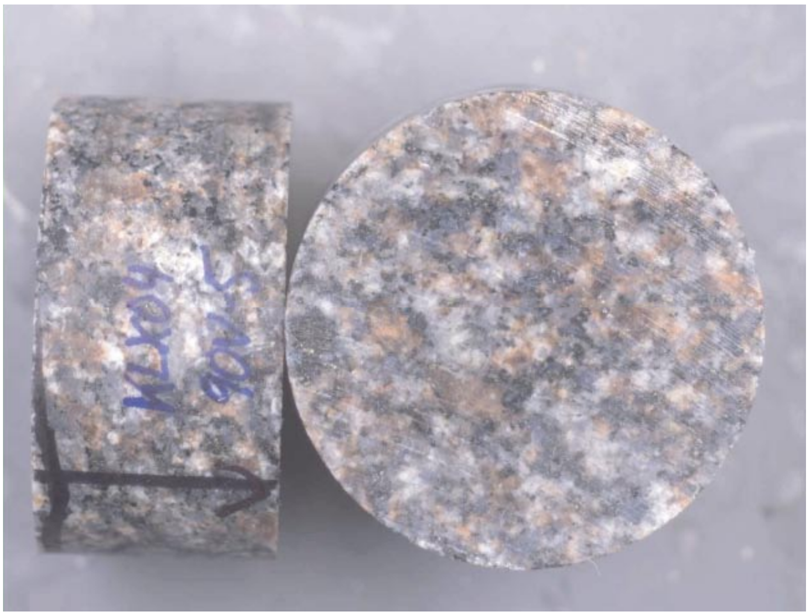

Figure 5-5. *Specimens X04A-90V-05.*

Table 5-9. Porosity, wet and dry density of specimens X04A-90V-05, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X04A-90V-05 Sec low: 308.26	2,676	2,670	0.6

Table 5-10. Thermal properties of sample X04A-90V-05 at ambient temperature.

X04A-90V-05 Sec low: 308.26	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.12	1.48	2.11
Standard deviation	0.003	0.005	0.008

Sample X04A-90V-07

Figure 5-6. *Specimens X04A-90V-07.*

Table 5-11. Porosity, wet and dry density of specimens X04A-90V-07, average values.

Sample	Density, wet (kg/m^3)	Density, dry (kg/m^3)	Porosity (%)
X04A-90V-07 Sec low: 562.14	2,718	2,713	0.5

Table 5-12. Thermal properties of sample X04A-90V-07 at different temperatures.

X04A-90V-07 Sec low: 562.14	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity (MJ/(m^3, K))
	20°C		
Mean value	2.58	1.10	2.34
Standard deviation	0.001	0.002	0.006
	50°C		
Mean value	2.58	1.02	2.53
Standard deviation	0.003	0.003	0.008
	80°C		
Mean value	2.55	0.96	2.67
Standard deviation	0.002	0.003	0.008

Sample X04A-90V-08

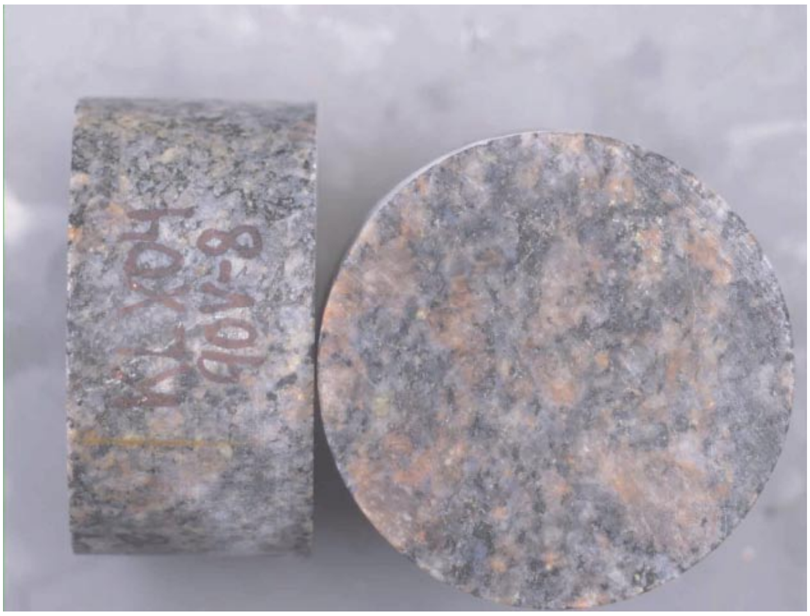

Figure 5-7. Specimens X04A-90V-08.

Table 5-13. Porosity, wet and dry density of specimens X04A-90V-08, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X04A-90V-08 Sec low: 562.2	2,707	2,701	0.6

Table 5-14. Thermal properties of sample X04A-90V-08 at different temperatures.

X04A-90V-08 Sec low: 562.2	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	2.71	1.31	2.07
Standard deviation	0.005	0.006	0.011
	50°C		
Mean value	2.69	1.19	2.27
Standard deviation	0.002	0.005	0.011
	80°C		
Mean value	2.58	1.11	2.32
Standard deviation	0.006	0.007	0.019

Sample X04A-90V-10

Figure 5-8. *Specimens X04A-90V-10.*

Table 5-15. Porosity, wet and dry density of specimens X04A-90V-10, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X04A-90V-10 Sec low: 567.25	2,756	2,749	0.7

Table 5-16. Thermal properties of sample X04A-90V-10 at different temperatures.

X04A-90V-10 Sec low: 567.25	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	2.48	1.05	2.38
Standard deviation	0.002	0.003	0.008
	50°C		
Mean value	2.50	0.98	2.56
Standard deviation	0.002	0.002	0.005
	80°C		
Mean value	2.47	0.91	2.71
Standard deviation	0.001	0.009	0.026

Sample X04A-90V-11

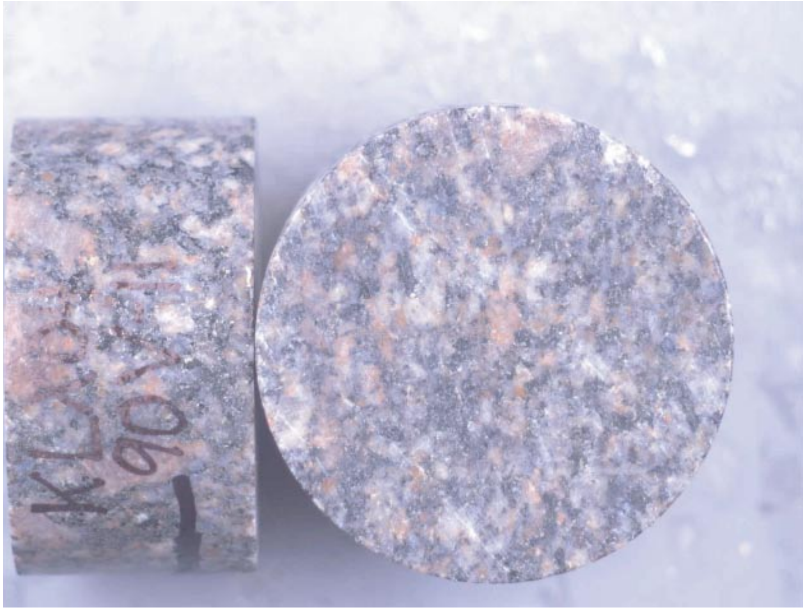

Figure 5-9. *Specimens X04A-90V-11.*

Table 5-17. Porosity, wet and dry density of specimens X04A-90V-11, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X04A-90V-11 Sec low: 567.31	2,731	2,724	0.8

Table 5-18. Thermal properties of sample X04A-90V-11 at different temperatures.

X04A-90V-11 Sec low: 567.31	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	2.55	1.05	2.43
Standard deviation	0.004	0.004	0.012
	50°C		
Mean value	2.54	0.98	2.61
Standard deviation	0.009	0.009	0.015
	80°C		
Mean value	2.53	0.93	2.72
Standard deviation	0.001	0.005	0.014

Sample X04A-90V-12

Figure 5-10. *Specimens X04A-90V-12.*

Table 5-19. Porosity, wet and dry density of specimens X04A-90V-12, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X04A-90V-12 Sec low: 567.37	2,732	2,726	0.6

Table 5-20. Thermal properties of sample X04A-90V-12 at different temperatures.

X04A-90V-12 Sec low: 567.37	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	2.47	1.11	2.23
Standard deviation	0.002	0.005	0.012
	50°C		
Mean value	2.46	1.03	2.39
Standard deviation	0.002	0.006	0.015
	80°C		
Mean value	2.42	0.97	2.51
Standard deviation	0.005	0.002	0.006

Sample X04A-90V-13

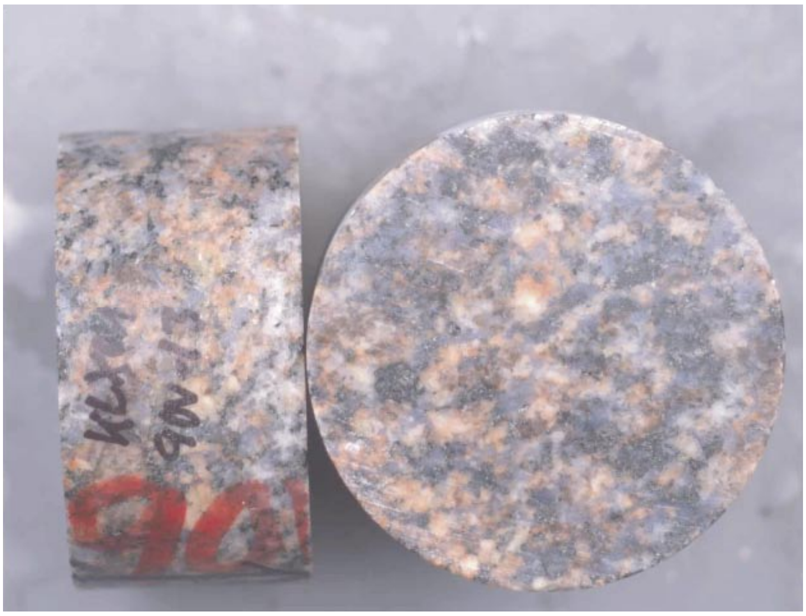

Figure 5-11. *Specimens X04A-90V-13.*

Table 5-21. Porosity, wet and dry density of specimens X04A-90V-13, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X04A-90V-13	2,682	2,677	0.5
Sec low: 739.54			

Table 5-22. Thermal properties of sample X04A-90V-13 at ambient temperature.

X04A-90V-13 Sec low: 739.54	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.27	1.36	2.40
Standard deviation	0.007	0.007	0.010

Sample X04A-90V-14

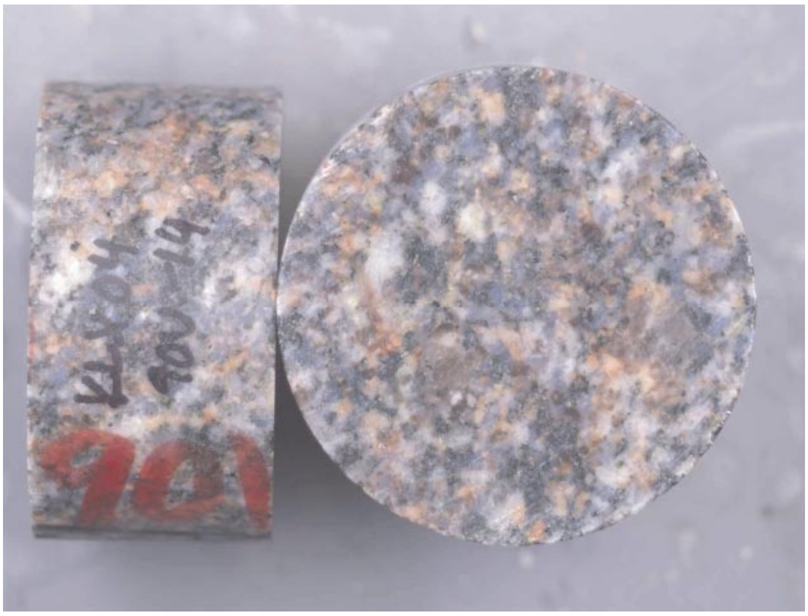

Figure 5-12. *Specimens X04A-90V-14.*

Table 5-23. Porosity, wet and dry density of specimens X04A-90V-14, average values.

Sample	Density, wet (kg/m^3)	Density, dry (kg/m^3)	Porosity (%)
X04A-90V-14 Sec low: 739.6	2,680	2,675	0.5

Table 5-24. Thermal properties of sample X04A-90V-14 at ambient temperature.

X04A-90V-14 Sec low: 739.6	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity (MJ/(m^3, K))
	20°C		
Mean value	3.16	1.49	2.13
Standard deviation	0.002	0.010	0.015

Sample X04A-90V-15

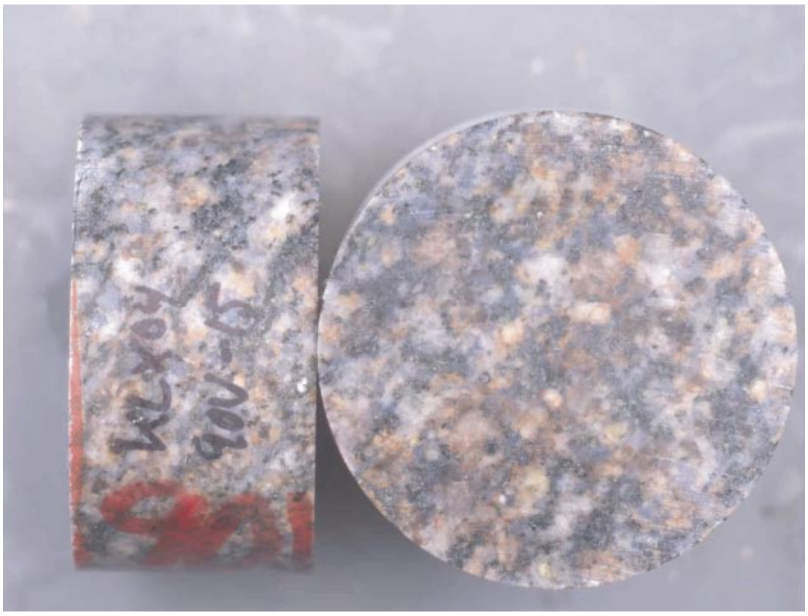

Figure 5-13. *Specimens X04A-90V-15.*

Table 5-25. Porosity, wet and dry density of specimens X04A-90V-15, average values.

Sample	Density, wet (kg/m^3)	Density, dry (kg/m^3)	Porosity (%)
X04A-90V-15	2,680	2,675	0.6
Sec low: 739.66			

Table 5-26. Thermal properties of sample X04A-90V-15 at ambient temperature.

X04A-90V-15 Sec low: 739.66	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity (MJ/(m^3, K))
	20°C		
Mean value	3.08	1.45	2.13
Standard deviation	0.002	0.005	0.008

Sample X04A-90V-16

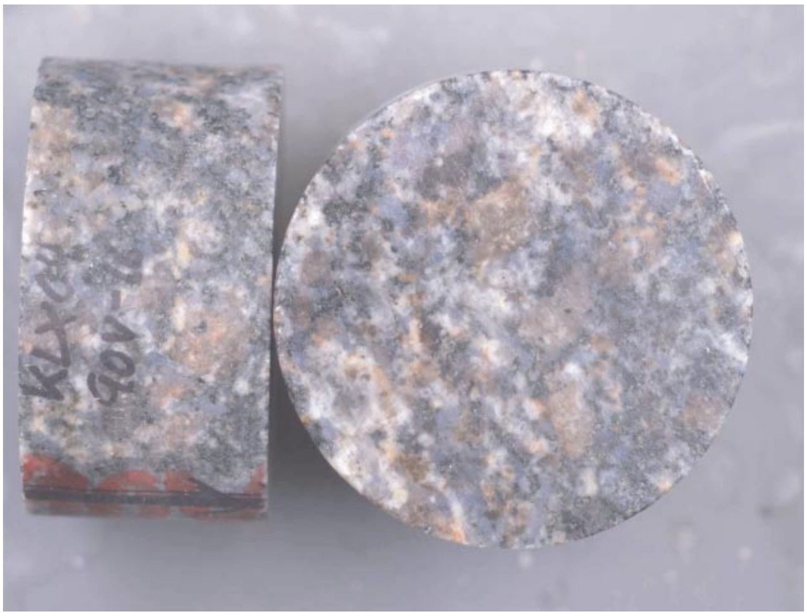

Figure 5-14. Specimens X04A-90V-16.

Table 5-27. Porosity, wet and dry density of specimens X04A-90V-16, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X04A-90V-16	2,681	2,675	0.5
Sec low: 746.45			

Table 5-28. Thermal properties of sample X04A-90V-16 at ambient temperature.

X04A-90V-16 Sec low: 746.45	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.13	1.52	2.06
Standard deviation	0.005	0.011	0.015

Sample X04A-90V-17

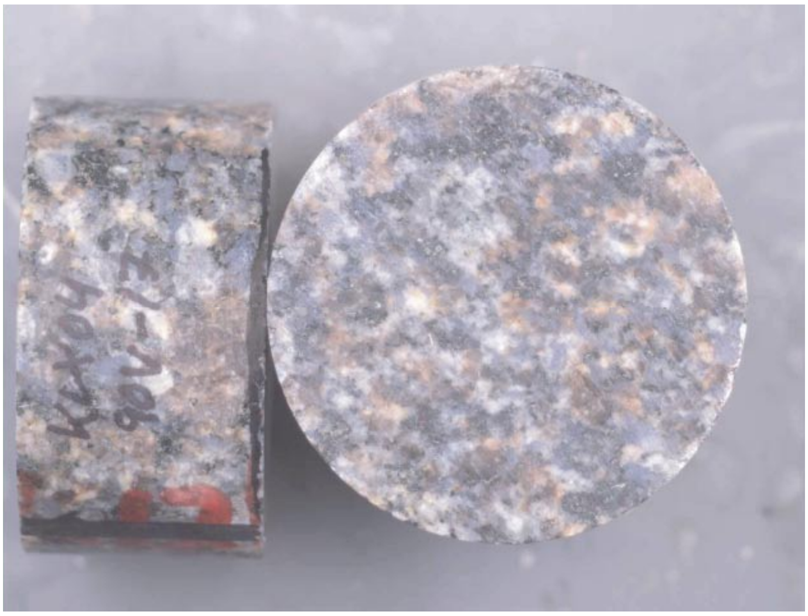

Figure 5-15. *Specimens X04A-90V-17.*

Table 5-29. Porosity, wet and dry density of specimens X04A-90V-17, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X04A-90V-17 Sec low: 746.51	2,675	2,670	0.5

Table 5-30. Thermal properties of sample X04A-90V-17 at ambient temperature.

X04A-90V-17 Sec low: 746.51	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.24	1.41	2.30
Standard deviation	0.003	0.005	0.007

5.1.2 Results for the entire test series

Table 5-31 to Table 5-33 show the mean value of five repeated measurements of the thermal properties. Standard deviation at different temperature levels is shown in Table 5-34 to Table 5-36.

Thermal conductivity and thermal diffusivity of specimens at different depth at 20°C were in the range of 2.72–3.32 W/(m, K) and 1.31–1.93 mm^2/s respectively. At 50°C, thermal conductivity and thermal diffusivity of specimens at different depth were in the range of 2.75–3.27 W/(m, K) and 1.22–1.64 mm^2/s respectively and finally at 80°C, thermal conductivity and thermal diffusivity of specimens were in the range of 2.69–3.10 W/(m, K) and 1.13–1.45 mm^2/s respectively.

Table 5-31. 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))
X04A-90V-01	3.43	1.61	2.13
X04A-90V-02	3.40	1.50	2.26
X04A-90V-03	3.30	1.67	1.97
X04A-90V-04	3.18	1.38	2.30
X04A-90V-05	3.12	1.48	2.11
Mean value, level 310	3.29	1.53	2.15
X04A-90V-07	2.58	1.10	2.34
X04A-90V-08	2.71	1.31	2.07
X04A-90V-10	2.48	1.05	2.38
X04A-90V-11	2.55	1.05	2.43
X04A-90V-12	2.47	1.11	2.23
Mean value, level 565	2.56	1.12	2.29
X04A-90V-13	3.27	1.36	2.40
X04A-90V-14	3.16	1.49	2.13
X04A-90V-15	3.08	1.45	2.13
X04A-90V-16	3.13	1.52	2.06
X04A-90V-17	3.24	1.41	2.30
Mean value, level 745	3.18	1.44	2.21

Table 5-32. 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))
X04A-90V-07	2.58	1.02	2.53
X04A-90V-08	2.69	1.19	2.27
X04A-90V-10	2.50	0.98	2.56
X04A-90V-11	2.54	0.98	2.61
X04A-90V-12	2.46	1.03	2.39
Mean value, level 500	2.55	1.04	2.47

Table 5-33. 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))
X04A-90V-07	2.55	0.96	2.67
X04A-90V-08	2.58	1.11	2.32
X04A-90V-10	2.47	0.91	2.71
X04A-90V-11	2.53	0.93	2.72
X04A-90V-12	2.42	0.97	2.51
Mean value, level 500	2.51	0.97	2.59

Table 5-34. Standard deviation of measured values at 20°C.

Sample identification	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity (MJ/(m^3, K))
X04A-90V-01	0.005	0.006	0.011
X04A-90V-02	0.002	0.002	0.003
X04A-90V-03	0.012	0.018	0.017
X04A-90V-04	0.005	0.007	0.014
X04A-90V-05	0.003	0.005	0.008
X04A-90V-07	0.001	0.002	0.006
X04A-90V-08	0.005	0.006	0.011
X04A-90V-10	0.002	0.003	0.008
X04A-90V-11	0.004	0.004	0.012
X04A-90V-12	0.002	0.005	0.012
X04A-90V-13	0.007	0.007	0.010
X04A-90V-14	0.002	0.010	0.015
X04A-90V-15	0.002	0.005	0.008
X04A-90V-16	0.005	0.011	0.015
X04A-90V-17	0.003	0.005	0.007

Table 5-35. Standard deviation of measured values at 50°C.

Sample identification	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity (MJ/(m^3, K))
X04A-90V-07	0.003	0.003	0.008
X04A-90V-08	0.002	0.005	0.011
X04A-90V-10	0.002	0.002	0.005
X04A-90V-11	0.009	0.009	0.015
X04A-90V-12	0.002	0.006	0.015

Table 5-36. Standard deviation of measured values at 80°C.

Sample identification	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity ($MJ/(m^3, K)$)
X04A-90V-07	0.002	0.003	0.008
X04A-90V-08	0.006	0.007	0.019
X04A-90V-10	0.001	0.009	0.026
X04A-90V-11	0.001	0.005	0.014
X04A-90V-12	0.005	0.002	0.006

5.1.2.1 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 5-16 to Figure 5-20.

Maximum variation of thermal conductivity in the temperature range 20°C to 80°C was 5% for sample X04A-90V-08 and maximum variation of heat capacity in the same temperature range was about 18% for sample X04A-90V-08.

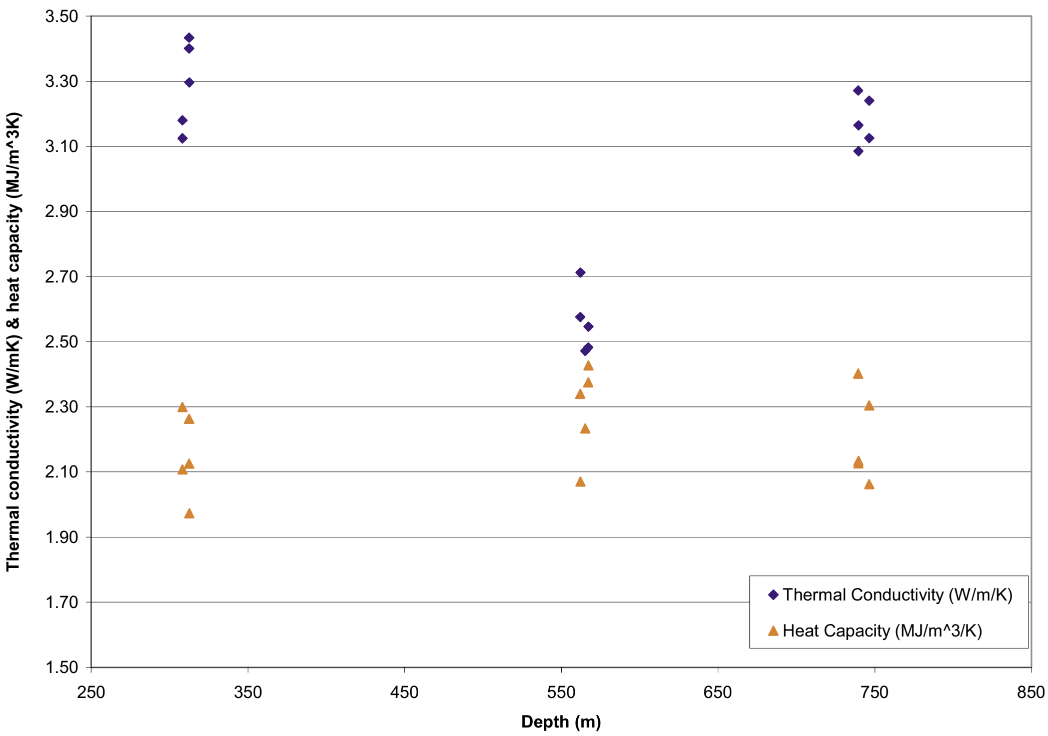

Figure 5-16. Thermal conductivity and heat capacity at different depth at 20°C.

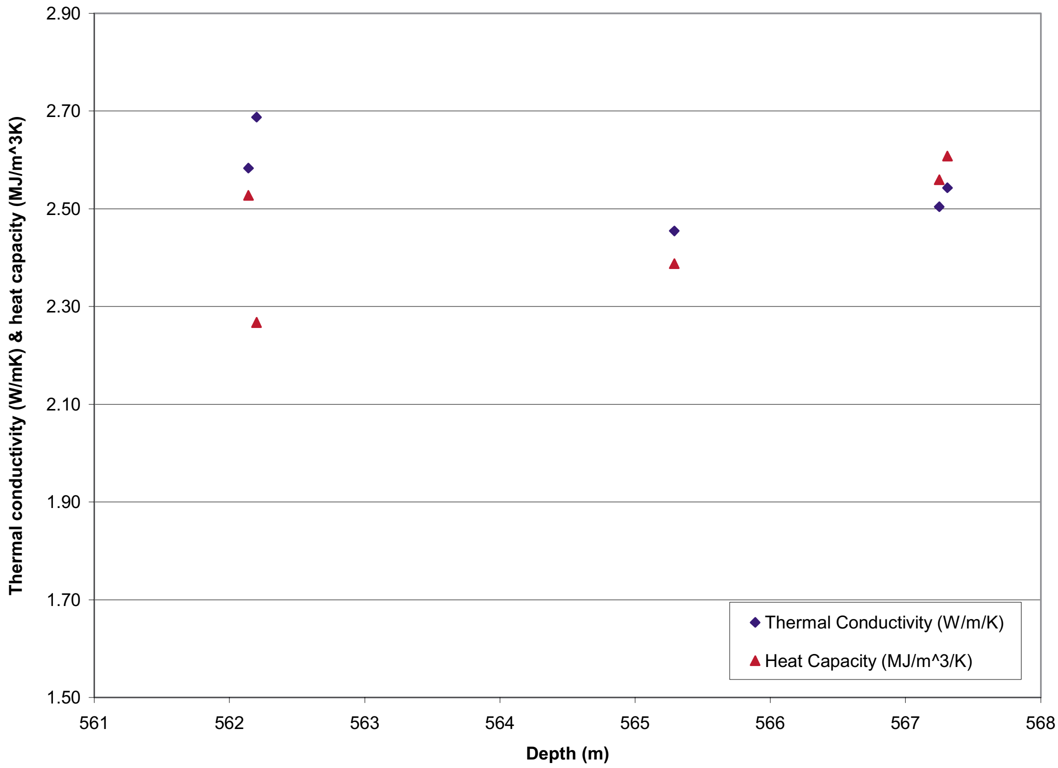

***Figure 5-17.** Thermal conductivity and heat capacity at different depth at 50°C.*

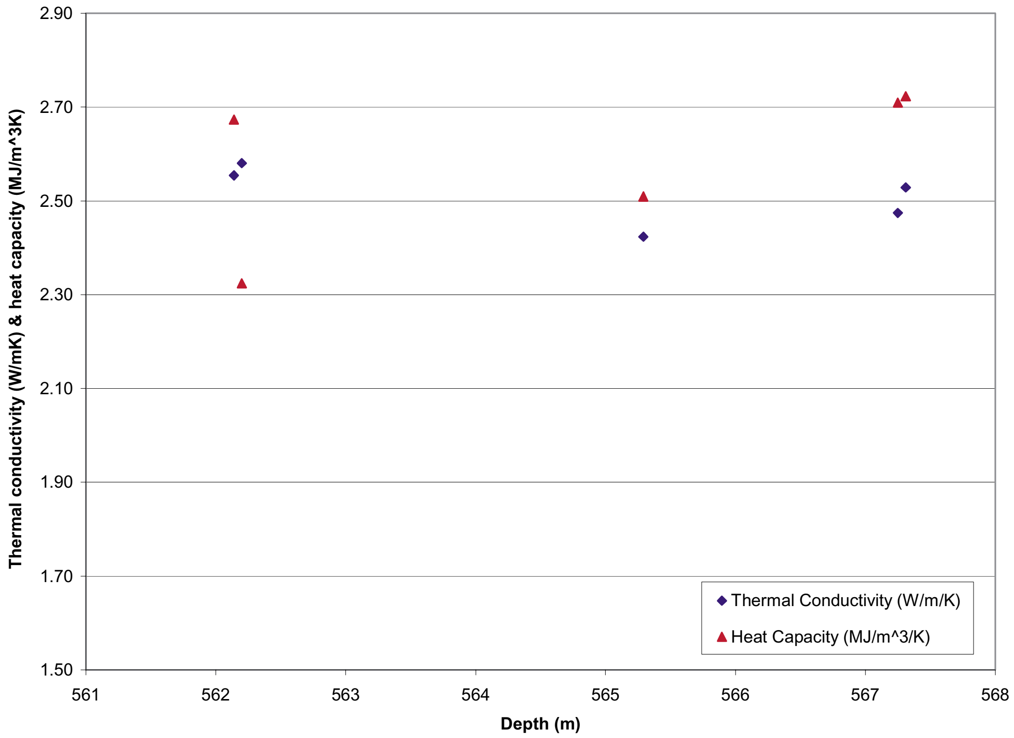

***Figure 5-18.** Thermal conductivity and heat capacity at different depth at 80°C.*

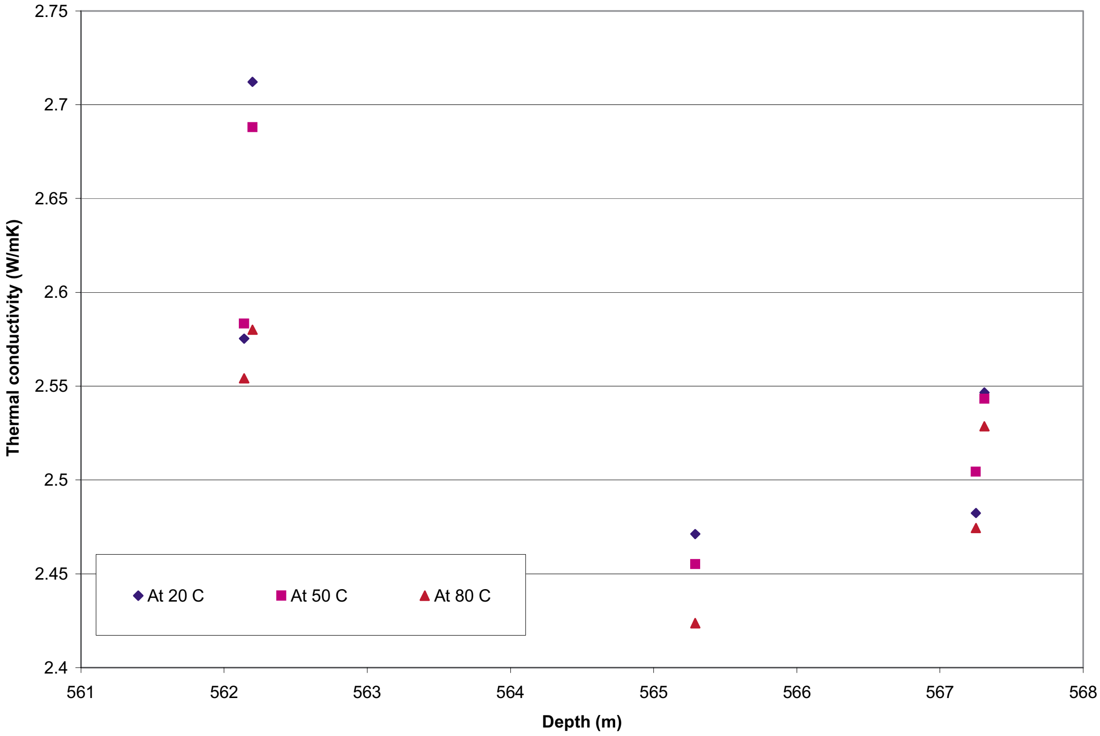

Figure 5-19. *Thermal conductivity at different depth and at different temperatures.*

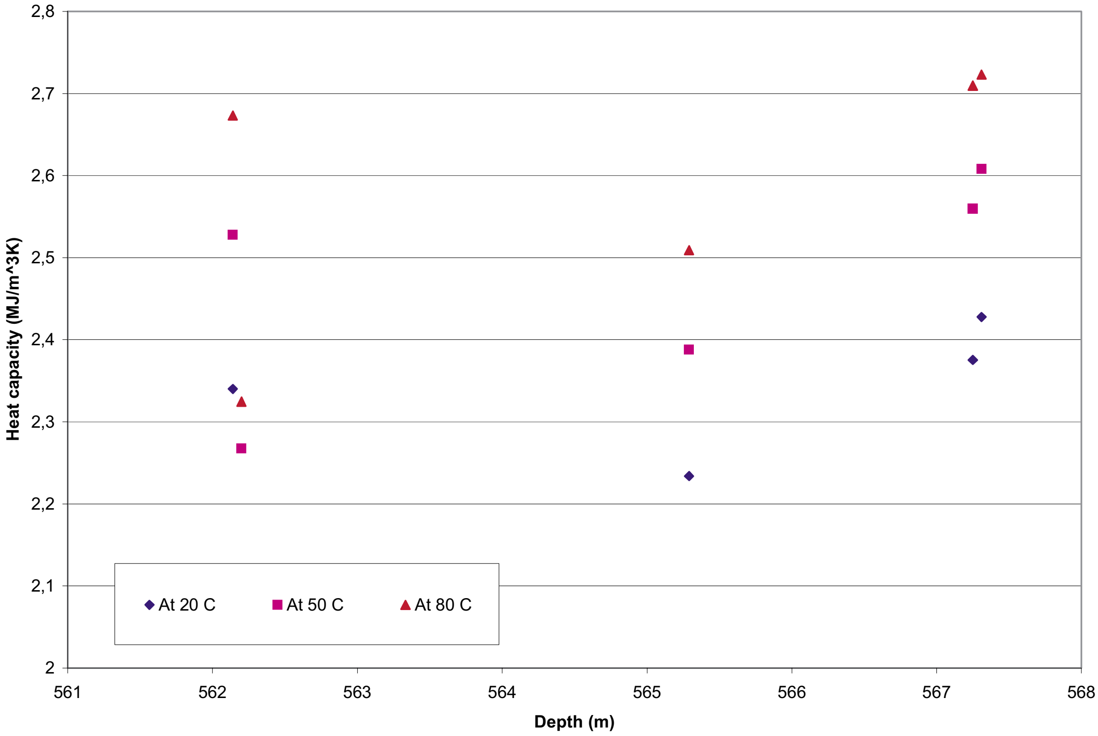

Figure 5-20. *Heat capacity at different depth and at different temperatures.*

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 secup in Table 5-37). The modal analyses were done in order to calculate the thermal properties based on the specimen's mineralogical composition.

Table 5-37. Mineralogical composition (in vol. %) of the investigated specimens from KLX04A, 500 points are counted on each specimen.

Identification	Sampling depth (Sec low)	Qtz	Kfs	Pl	Bt	Sph	Op	As	Am	Ep
KLX04A-200-1	312.34	28	35	33	3	0.6	–	0.4	–	0.6
KLX04A-200-2	308.14	31	30	28	8	0.6	0.8	0.2	–	0.8
KLX04A-200-3	562.08	20	14	49	14	1	0.6	0.6	–	1
KLX04A-200-4	567.2	16	10	51	15	1	1	0.6	1	3
KLX04A-200-5	739.48	23	20	44	8	0.6	0.6	1	–	2
KLX04A-200-6	746.39	21	20	46	10	0.4	0.6	0.4	0.6	1

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

Qtz = Quartz, Kfs = K-feldspar, Pl = Plagioclase, Bt = Biotite, Sph = Sphene, Op = opaque minerals, As = Accessory minerals, Am = Amphibole, Ep = Epidote. Accessory minerals are Chlorite, Calcite, Apatite and Zircon.

5.3 Discussion

The following deviation to the plans occurred:

Sample 9 was too short to produce test specimens. Reserve sample 12 was used instead.

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

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 1.5
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:		13.54 W/(m, K)	± 0.07%
Thermal Diffusivity:	3.535 mm^2/s	± 0.13%	
Heat Capacity:	3.830 $MJ/(m^3, K)$	± 0.17%	

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

Borås 23/08 2004

Bijan Adl-Zarrabi

Appendix B

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

Measurement number	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
X04A-90V-01			
1	3.43	1.61	2.13
2	3.43	1.61	2.13
3	3.43	1.63	2.11
4	3.44	1.61	2.13
5	3.44	1.61	2.14
X04A-90V-02			
1	3.40	1.50	2.26
2	3.40	1.50	2.26
3	3.40	1.50	2.27
4	3.40	1.50	2.26
5	3.40	1.50	2.27
X04A-90V-03			
1	3.29	1.65	1.99
2	3.29	1.67	1.97
3	3.32	1.70	1.95
4	3.29	1.66	1.99
5	3.29	1.67	1.96
X04A-90V-04			
1	3.18	1.38	2.30
2	3.19	1.38	2.30
3	3.18	1.40	2.28
4	3.18	1.38	2.31
5	3.17	1.38	2.30
X04A-90V-05			
1	3.12	1.49	2.10
2	3.13	1.48	2.11
3	3.13	1.48	2.11
4	3.13	1.48	2.12
5	3.12	1.48	2.10
X04A-90V-07			
1	2.58	1.10	2.34
2	2.58	1.10	2.34
3	2.57	1.10	2.34
4	2.58	1.10	2.35
5	2.58	1.10	2.34
X04A-90V-08			
1	2.72	1.32	2.06
2	2.72	1.30	2.09
3	2.71	1.31	2.07
4	2.71	1.31	2.06
5	2.71	1.31	2.06

Table B-1 (continues). Thermal properties of samples at 20°C.

Measurement number	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity (MJ/(m^3, K))
X04A-90V-10			
1	2.48	1.04	2.38
2	2.49	1.04	2.39
3	2.48	1.05	2.37
4	2.48	1.05	2.37
5	2.48	1.05	2.37
X04A-90V-11			
1	2.54	1.05	2.43
2	2.55	1.05	2.43
3	2.55	1.05	2.44
4	2.55	1.05	2.44
5	2.54	1.06	2.41
X04A-90V-12			
1	2.47	1.10	2.24
2	2.47	1.11	2.23
3	2.47	1.10	2.25
4	2.47	1.11	2.22
5	2.47	1.11	2.23
X04A-90V-13			
1	3.27	1.36	2.41
2	3.27	1.36	2.40
3	3.28	1.37	2.39
4	3.27	1.35	2.41
5	3.26	1.36	2.39
X04A-90V-14			
1	3.17	1.49	2.12
2	3.16	1.50	2.11
3	3.16	1.49	2.13
4	3.17	1.48	2.14
5	3.16	1.48	2.14
X04A-90V-15			
1	3.08	1.45	2.13
2	3.08	1.45	2.13
3	3.09	1.44	2.14
4	3.08	1.44	2.14
5	3.08	1.44	2.14
X04A-90V-16			
1	3.13	1.53	2.04
2	3.13	1.51	2.07
3	3.13	1.51	2.08
4	3.12	1.51	2.06
5	3.12	1.51	2.07
X04A-90V-17			
1	3.24	1.41	2.30
2	3.24	1.41	2.30
3	3.24	1.41	2.30
4	3.24	1.40	2.31
5	3.24	1.41	2.30

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))
X04A-90V-07			
1	2.59	1.02	2.53
2	2.58	1.02	2.54
3	2.58	1.02	2.52
4	2.58	1.02	2.53
5	2.58	1.03	2.52
F01A-90V-08			
1	2.69	1.18	2.28
2	2.69	1.19	2.26
3	2.69	1.19	2.26
4	2.69	1.19	2.26
5	2.69	1.18	2.27
X04A-90V-10			
1	2.50	0.98	2.55
2	2.50	0.98	2.57
3	2.51	0.98	2.56
4	2.50	0.98	2.56
5	2.50	0.98	2.56
X04A-90V-11			
1	2.53	0.96	2.63
2	2.55	0.97	2.61
3	2.55	0.98	2.60
4	2.55	0.98	2.60
5	2.55	0.98	2.60
X04A-90V-12			
1	2.45	1.03	2.38
2	2.45	1.03	2.37
3	2.46	1.03	2.38
4	2.46	1.02	2.40
5	2.46	1.02	2.40

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))
X04A-90V-07			
1	2.55	0.95	2.69
2	2.56	0.96	2.67
3	2.56	0.96	2.67
4	2.55	0.96	2.67
5	2.55	0.96	2.67
F01A-90V-08			
1	2.59	1.10	2.35
2	2.58	1.11	2.34
3	2.58	1.11	2.31
4	2.57	1.12	2.30
5	2.58	1.11	2.33
X04A-90V-10			
1	2.47	0.92	2.68
2	2.48	0.92	2.68
3	2.47	0.91	2.73
4	2.47	0.91	2.73
5	2.47	0.91	2.72
X04A-90V-11			
1	2.53	0.92	2.73
2	2.53	0.93	2.71
3	2.53	0.94	2.71
4	2.53	0.92	2.73
5	2.53	0.93	2.73
X04A-90V-12			
1	2.43	0.97	2.51
2	2.43	0.97	2.51
3	2.42	0.96	2.52
4	2.42	0.97	2.50
5	2.42	0.96	2.51

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
X04A-90V-01			
1	20	0.78	32– 200
2	20	0.78	27– 200
3	20	0.79	28– 200
4	20	0.78	24– 200
5	20	0.78	26– 200
X04A-90V-02			
1	20	0.73	41– 199
2	20	0.72	31– 198
3	20	0.72	34– 199
4	20	0.73	34– 200
5	20	0.73	33– 200
X04A-90V-03			
1	20	0.80	27– 200
2	20	0.81	22– 200
3	20	0.82	38– 200
4	20	0.80	29– 200
5	20	0.81	30– 200
X04A-90V-04			
1	20	0.67	56– 200
2	20	0.67	55– 200
3	20	0.68	58– 200
4	20	0.67	56– 200
5	20	0.67	59– 200
X04A-90V-05			
1	20	0.72	64– 200
2	20	0.72	66– 200
3	20	0.71	66– 198
4	20	0.72	64– 200
5	20	0.72	66– 200
X04A-90V-07			
1	20	0.53	56– 200
2	20	0.53	53– 200
3	20	0.53	55– 200
4	20	0.53	58– 200
5	20	0.53	53– 200
X04A-90V-08			
1	20	0.64	35– 200
2	20	0.63	32– 200
3	20	0.63	35– 200
4	20	0.64	35– 200
5	20	0.64	29– 200

Table C-1 (continues). 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
X04A-90V-10			
1	20	0.51	29– 200
2	20	0.51	20– 200
3	20	0.51	20– 200
4	20	0.51	21– 199
5	20	0.51	20– 200
X04A-90V-11			
1	20	0.51	31– 200
2	20	0.51	29– 200
3	20	0.51	35– 200
4	20	0.51	35– 200
5	20	0.51	29– 200
X04A-90V-12			
1	20	0.54	26– 200
2	20	0.54	21– 200
3	20	0.53	35– 200
4	20	0.54	33– 200
5	20	0.53	34– 198
X04A-90V-13			
1	20	0.66	27– 200
2	20	0.66	26– 200
3	20	0.67	30– 200
4	20	0.66	27– 200
5	20	0.66	23– 200
X04A-90V-14			
1	20	0.72	28– 200
2	20	0.73	27– 200
3	20	0.72	26– 200
4	20	0.72	30– 200
5	20	0.72	31– 200
X04A-90V-15			
1	20	0.70	59– 200
2	20	0.70	53– 200
3	20	0.70	58– 200
4	20	0.70	63– 200
5	20	0.70	58– 200
X04A-90V-16			
1	20	0.74	31– 200
2	20	0.73	23– 200
3	20	0.73	20– 200
4	20	0.73	32– 200
5	20	0.73	26– 200
X04A-90V-17			
1	20	0.68	80– 200
2	20	0.69	71– 200
3	20	0.68	74– 200
4	20	0.68	84– 200
5	20	0.68	76– 200

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
X04A-90V-07			
1	20	0.50	79– 200
2	20	0.49	59– 200
3	20	0.50	44– 200
4	20	0.50	55– 200
5	20	0.50	56– 200
F01A-90V-08			
1	20	0.57	35– 200
2	20	0.58	39– 200
3	20	0.58	37– 200
4	20	0.58	31– 200
5	20	0.57	29– 200
X04A-90V-10			
1	20	0.48	27– 200
2	20	0.47	28– 200
3	20	0.48	29– 200
4	20	0.48	27– 200
5	20	0.47	26– 200
X04A-90V-11			
1	20	0.46	73– 198
2	20	0.47	57– 198
3	20	0.48	40– 200
4	20	0.48	40– 200
5	20	0.48	40– 200
X04A-90V-12			
1	20	0.50	28– 200
2	20	0.50	32– 200
3	20	0.50	37– 200
4	20	0.50	34– 200
5	20	0.50	40– 200

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
X04A-90V-07			
1	20	0.46	59– 200
2	20	0.46	42– 200
3	20	0.46	31– 200
4	20	0.46	26– 200
5	20	0.46	29– 200
F01A-90V-08			
1	20	0.54	35– 200
2	20	0.54	29– 200
3	20	0.54	27– 200
4	20	0.54	31– 200
5	20	0.54	32– 200
X04A-90V-10			
1	20	0.45	30– 200
2	20	0.45	30– 200
3	20	0.44	30– 200
4	20	0.44	30– 200
5	20	0.44	30– 200
X04A-90V-11			
1	20	0.44	24– 195
2	20	0.45	23– 200
3	20	0.45	24– 200
4	20	0.45	25– 200
5	20	0.45	29– 200
X04A-90V-12			
1	20	0.47	26– 200
2	20	0.47	25– 200
3	20	0.47	26– 200
4	20	0.47	24– 200
5	20	0.47	29– 200