P-04-258

Oskarshamn site investigation

Drill hole KLX02

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

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October 2004

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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 KLX02, Laxemar, were measured at ambient and elevated temperature. The rock type of all samples is 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 2.72–3.32 W/(m, K) and 1.31–1.93 mm^2/s respectively. 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.

Sammanfattning

Termiska egenskaper hos femton provkroppar från borrhål KLX02, 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 2,72–3,32 W/(m, K) respektive 1,31–1,93 mm^2/s. Vid 80 °C var den termiska konduktiviteten och den termiska diffusiviteten hos provkropparna i intervallet 2,69–3,10 W/(m, K) respektive 1,13–1,45 mm^2/s.

Contents

1 Introduction

The objective of this investigation was to measure thermal properties of borehole KLX02, 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 400–03-092 (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 seven 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 February 2004. The testing was performed during August–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).

Figure 1-1. *Location of the drill hole KLX02 at the Laxemar site.*

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 KLX02 in Laxemar. The specimens were sampled on three levels in the drill hole: 315 m, 500 m, and 740 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).

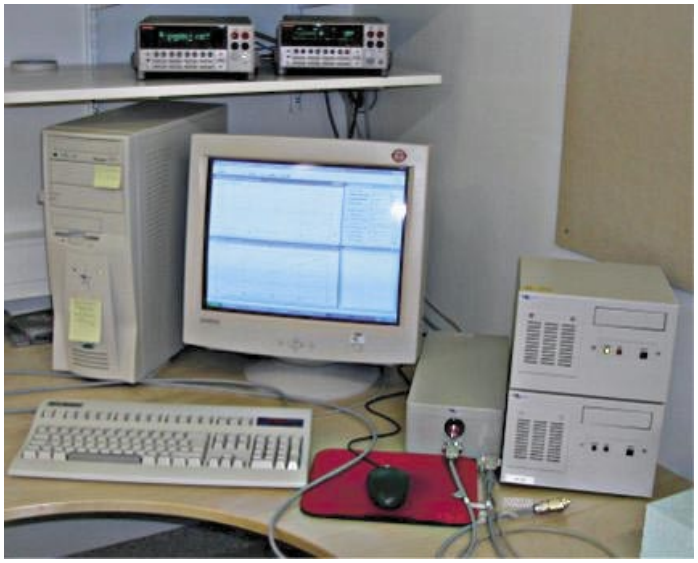

Figure 3-1. *TPS-apparatus with source meter, multi-meter, bridge, and computer.*

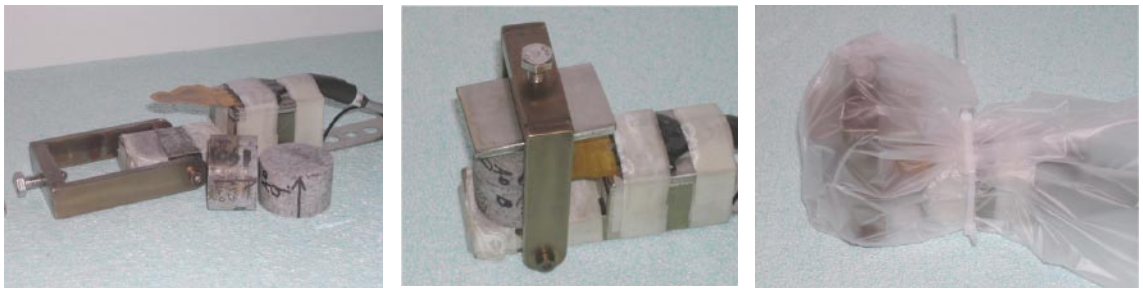

Figure 3-2. *Specimens prior to mounting (left), mounted in stainless sample holder (middle), and sample holder with mounted specimens wrapped in plastic (right).*

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 KLX02, Laxemar, Sweden. The first level was between 314 m and 315 m, the second level was between 492 m and 502 m, and the third level between 738 m and 740 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 KLX02 and in the SICADA database at SKB.

Shortened sample identification X02-90V 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)
KLX02-90V-1	Ävrö granite	314.39
KLX02-90V-2	Ävrö granite	314.45
KLX02-90V-3	Ävrö granite	314.51
KLX02-90V-4	Ävrö granite	314.57
KLX02-90V-5	Ävrö granite	314.63
KLX02-90V-7	Ävrö granite	492.36
KLX02-90V-8	Ävrö granite	492.42
KLX02-90V-9	Ävrö granite	502.01
KLX02-90V-10	Ävrö granite	502.07
KLX02-90V-11	Ävrö granite	502.13
KLX02-90V-13	Ävrö granite	738.28
KLX02-90V-14	Ävrö granite	738.34
KLX02-90V-15	Ävrö granite	740.08
KLX02-90V-16	Ävrö granite	740.14
KLX02-90V-17	Ävrö granite	740.20

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 August–September 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 236) 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 X02-90V-01

Figure 5-1. *Specimens X02-90V-01.*

Table 5-1. Porosity, wet and dry density of specimens X02-90V-01, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-01	2,695	2,691	0.4
Sec low: 314.39			

Table 5-2. Thermal properties of sample X02-90V-01 at ambient temperature.

X02-90V-01 Sec low: 314.39	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.21	1.44	2.22
Standard deviation	0.006	0.009	0.018

Sample X02-90V-02

Figure 5-2. *Specimens X02-90V-02*

Table 5-3. Porosity, wet and dry density of specimens X02-90V-02, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-02 Sec low: 314.45	2,680	2,676	0.4

Table 5-4. Thermal properties of sample X02-90V-02 at ambient temperature.

X02-90V-02 Sec low: 314.45	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
		20°C	
Mean value	3.28	1.33	2.46
Standard deviation	0.007	0.007	0.017

Sample X02-90V-03

Figure 5-3. *Specimens X02-90V-03.*

Table 5-5. Porosity, wet and dry density of specimens X02-90V-03, average values.

Sample	Density, wet (kg/m^3)	Density, dry (kg/m^3)	Porosity (%)
X02-90V-03	2,684	2,681	0.3
Sec low: 314.51			

Table 5-6. Thermal properties of sample X02-90V-03 at ambient temperature.

X02-90V-03 Sec low: 314.51	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity (MJ/(m^3, K))
	20°C		
Mean value	3.09	1.32	2.35
Standard deviation	0.002	0.005	0.011

Sample X02-90V-04

Figure 5-4. *Specimens X02-90V-04.*

Table 5-7. Porosity, wet and dry density of specimens X02-90V-04, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-04 Sec low: 314.57	2,686	2,683	0.3

Table 5-8. Thermal properties of sample X02-90V-04 at ambient temperature.

X02-90V-04 Sec low: 314.57	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
		20°C	
Mean value	3.12	1.38	2.26
Standard deviation	0.007	0.011	0.023

Sample X02-90V-05

Figure 5-5. *Specimens X02-90V-05.*

Table 5-9. Porosity, wet and dry density of specimens X02-90V-05, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-05 Sec low: 314.63	2,686	2,682	0.3

Table 5-10. Thermal properties of sample X02-90V-05 at ambient temperature.

X02-90V-05 Sec low: 314.63	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.07	1.38	2.23
Standard deviation	0.002	0.003	0.005

Sample X02-90V-07

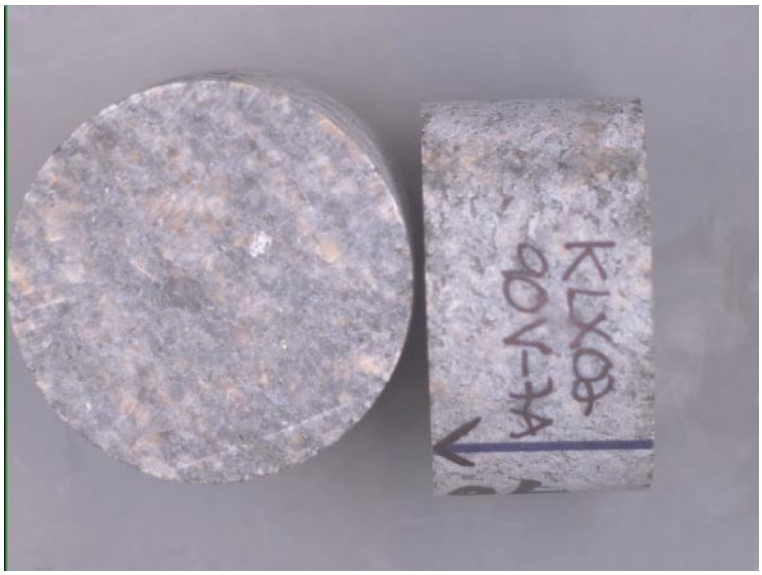

Figure 5-6. *Specimens X02-90V-07.*

Table 5-11. Porosity, wet and dry density of specimens X02-90V-07, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-07	2,693	2,690	0.3
Sec low: 492.36			

Table 5-12. Thermal properties of sample X02-90V-07 at different temperatures.

X02-90V-07 Sec low: 492.36	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.05	1.36	2.24
Standard deviation	0.003	0.004	0.007
	50°C		
Mean value	3.02	1.23	2.44
Standard deviation	0.003	0.005	0.010
	80°C		
Mean value	2.93	1.15	2.55
Standard deviation	0.005	0.008	0.021

Sample X02-90V-08

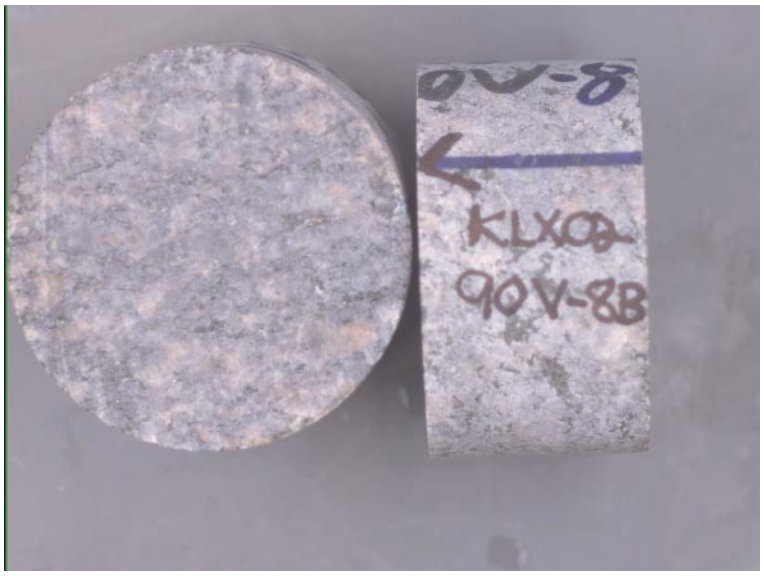

Figure 5-7. *Specimens X02-90V-08.*

Table 5-13. Porosity, wet and dry density of specimens X02-90V-08, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-08	2,692	2,688	0.4
Sec low: 492.42			

Table 5-14. Thermal properties of sample X02-90V-08 at different temperatures.

X02-90V-08 Sec low: 492.42	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.08	1.41	2.18
Standard deviation	0.003	0.002	0.005
	50°C		
Mean value	3.01	1.27	2.37
Standard deviation	0.003	0.002	0.004
	80°C		
Mean value	2.91	1.19	2.46
Standard deviation	0.003	0.005	0.011

Sample X02-90V-09

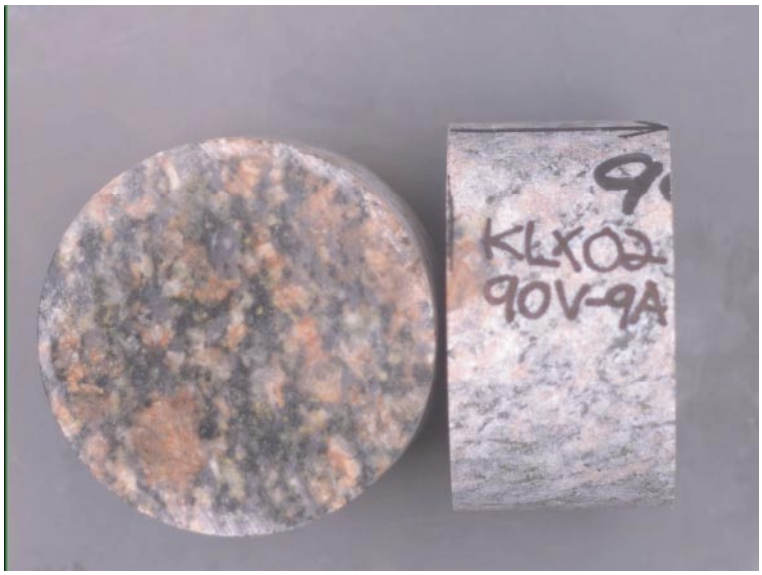

Figure 5-8. *Specimens X02-90V-09.*

Table 5-15. Porosity, wet and dry density of specimens X02-90V-09, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-09	2,690	2,685	0.5
Sec low: 502.01			

Table 5-16. Thermal properties of sample X02-90V-09 at different temperatures.

X02-90V-09 Sec low: 502.01	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.12	1.35	2.31
Standard deviation	0.002	0.003	0.004
	50°C		
Mean value	3.13	1.22	2.57
Standard deviation	0.002	0.003	0.006
	80°C		
Mean value	3.02	1.13	2.67
Standard deviation	0.007	0.004	0.013

Sample X02-90V-10

Figure 5-9. *Specimens X02-90V-10.*

Table 5-17. Porosity, wet and dry density of specimens X02-90V-10, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-10	2,680	2,676	0.5
Sec low: 502.07			

Table 5-18. Thermal properties of sample X02-90V-10 at different temperatures.

X02-90V-10 Sec low: 502.07	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.32	1.48	2.24
Standard deviation	0.004	0.004	0.006
	50°C		
Mean value	3.27	1.36	2.40
Standard deviation	0.005	0.007	0.010
	80°C		
Mean value	3.10	1.23	2.52
Standard deviation	0.006	0.003	0.009

Sample X02-90V-11

Figure 5-10. *Specimens X02-90V-11.*

Table 5-19. Porosity, wet and dry density of specimens X02-90V-11, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-11 Sec low: 502.13	2,673	2,668	0.5

Table 5-20. Thermal properties of sample X02-90V-11 at different temperatures.

X02-90V-11 Sec low: 502.13	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	2.72	1.93	1.41
Standard deviation	0.009	0.015	0.014
	50°C		
Mean value	2.75	1.64	1.67
Standard deviation	0.004	0.013	0.016
	80°C		
Mean value	2.69	1.45	1.86
Standard deviation	0.003	0.010	0.014

Sample X02-90V-13

Figure 5-11. *Specimens X02-90V-13.*

Table 5-21. Porosity, wet and dry density of specimens X02-90V-13, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-13 Sec low: 738.28	2,671	2,665	0.6

Table 5-22. Thermal properties of sample X02-90V-13 at ambient temperature.

X02-90V-13 Sec low: 738.28	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
		20°C	
Mean value	3.25	1.31	2.47
Standard deviation	0.001	0.009	0.016

Sample X02-90V-14

Figure 5-12. *Specimens X02-90V-14.*

Table 5-23. Porosity, wet and dry density of specimens X02-90V-14, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-14 Sec low: 738.34	2,675	2,669	0.6

Table 5-24. Thermal properties of sample X02-90V-14 at ambient temperature.

X02-90V-14 Sec low: 738.34	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.10	1.50	2.07
Standard deviation	0.008	0.004	0.009

Sample X02-90V-15

Figure 5-13. *Specimens X02-90V-15.*

Table 5-25. Porosity, wet and dry density of specimens X02-90V-15, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-15 Sec low: 740.08	2,683	2,678	0.5

Table 5-26. Thermal properties of sample X02-90V-15 at ambient temperature.

X02-90V-15 Sec low: 740.08	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
		20°C	
Mean value	3.05	1.54	1.98
Standard deviation	0.014	0.012	0.023

Sample X02-90V-16

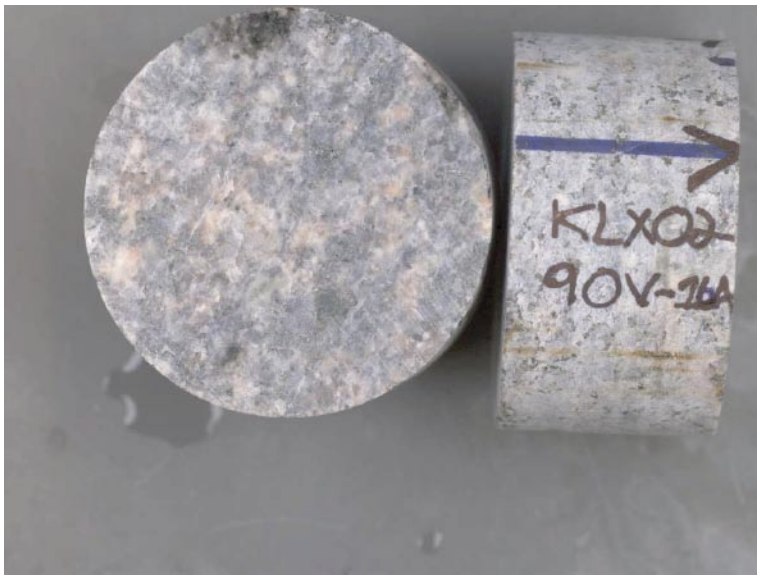

Figure 5-14. *Specimens X02-90V-16.*

Table 5-27. Porosity, wet and dry density of specimens X02-90V-16, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-16 Sec low: 740.14	2,680	2,675	0.5

Table 5-28. Thermal properties of sample X02-90V-16 at ambient temperature.

X02-90V-16 Sec low: 740.14	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.03	1.33	2.28
Standard deviation	0.006	0.008	0.013

Sample X02-90V-17

Figure 5-15. *Specimens X02-90V-17.*

Table 5-29. Porosity, wet and dry density of specimens X02-90V-17, average values.

Sample	Density, wet (kg/m³)	Density, dry (kg/m³)	Porosity (%)
X02-90V-17 Sec low: 740.2	2,684	2,679	0.5

Table 5-30. Thermal properties of sample X02-90V-17 at ambient temperature.

X02-90V-17 Sec low: 740.2	Conductivity (W/(m, K))	Diffusivity (mm²/s)	Heat capacity (MJ/(m³, K))
	20°C		
Mean value	3.10	1.31	2.37
Standard deviation	0.010	0.004	0.002

5.1.2 Results for the entire test series

Table 5-31–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–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 ($MJ/(m^3, K)$)
X02-90V-01	3.21	1.44	2.22
X02-90V-02	3.28	1.33	2.46
X02-90V-03	3.09	1.32	2.35
X02-90V-04	3.12	1.38	2.26
X02-90V-05	3.07	1.38	2.23
Mean value, level 315	3.16	1.37	2.30
X02-90V-07	3.05	1.36	2.24
X02-90V-08	3.08	1.41	2.18
X02-90V-09	3.12	1.35	2.31
X02-90V-10	3.32	1.48	2.24
X02-90V-11	2.72	1.93	1.41
Mean value, level 500	3.06	1.51	2.08
X02-90V-13	3.25	1.31	2.47
X02-90V-14	3.10	1.50	2.07
X02-90V-15	3.05	1.54	1.98
X02-90V-16	3.03	1.33	2.28
X02-90V-17	3.10	1.31	2.37
Mean value, level 740	3.10	1.40	2.24

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 ($MJ/(m^3, K)$)
X02-90V-07	3.02	1.23	2.44
X02-90V-08	3.01	1.27	2.37
X02-90V-09	3.13	1.22	2.57
X02-90V-10	3.27	1.36	2.40
X02-90V-11	2.75	1.64	1.67
Mean value, level 500	3.03	1.35	2.29

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 ($MJ/(m^3, K)$)
X02-90V-07	2.93	1.15	2.55
X02-90V-08	2.91	1.19	2.46
X02-90V-09	3.02	1.13	2.67
X02-90V-10	3.10	1.23	2.52
X02-90V-11	2.69	1.45	1.86
Mean value, level 500	2.93	1.23	2.41

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

Sample identification	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity ($MJ/(m^3, K)$)
X02-90V-01	0.006	0.009	0.018
X02-90V-02	0.007	0.007	0.017
X02-90V-03	0.002	0.005	0.011
X02-90V-04	0.007	0.011	0.023
X02-90V-05	0.002	0.003	0.005
X02-90V-07	0.003	0.004	0.007
X02-90V-08	0.003	0.002	0.005
X02-90V-09	0.002	0.003	0.004
X02-90V-10	0.004	0.004	0.006
X02-90V-11	0.009	0.015	0.014
X02-90V-13	0.001	0.009	0.016
X02-90V-14	0.008	0.004	0.009
X02-90V-15	0.014	0.012	0.023
X02-90V-16	0.006	0.008	0.013
X02-90V-17	0.010	0.004	0.002

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

Sample identification	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity ($MJ/(m^3, K)$)
X02-90V-07	0.003	0.005	0.010
X02-90V-08	0.003	0.002	0.004
X02-90V-09	0.002	0.003	0.006
X02-90V-10	0.005	0.007	0.010
X02-90V-11	0.004	0.013	0.016

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

Sample identification	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity ($MJ/(m^3, K)$)
X02-90V-07	0.005	0.008	0.021
X02-90V-08	0.003	0.005	0.011
X02-90V-09	0.007	0.004	0.013
X02-90V-10	0.006	0.003	0.009
X02-90V-11	0.003	0.010	0.014

5.1.4.1 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–Figure 5-20.

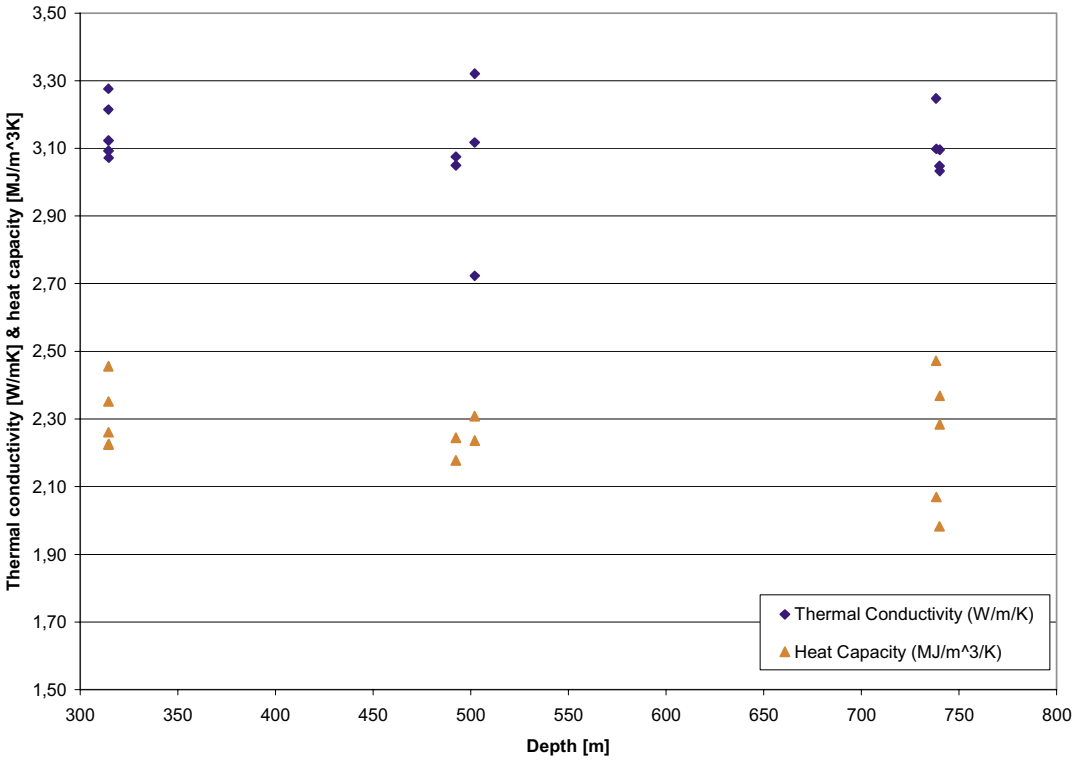

Figure 5-16. *Thermal conductivity and heat capacity at different depth at 20°C.*

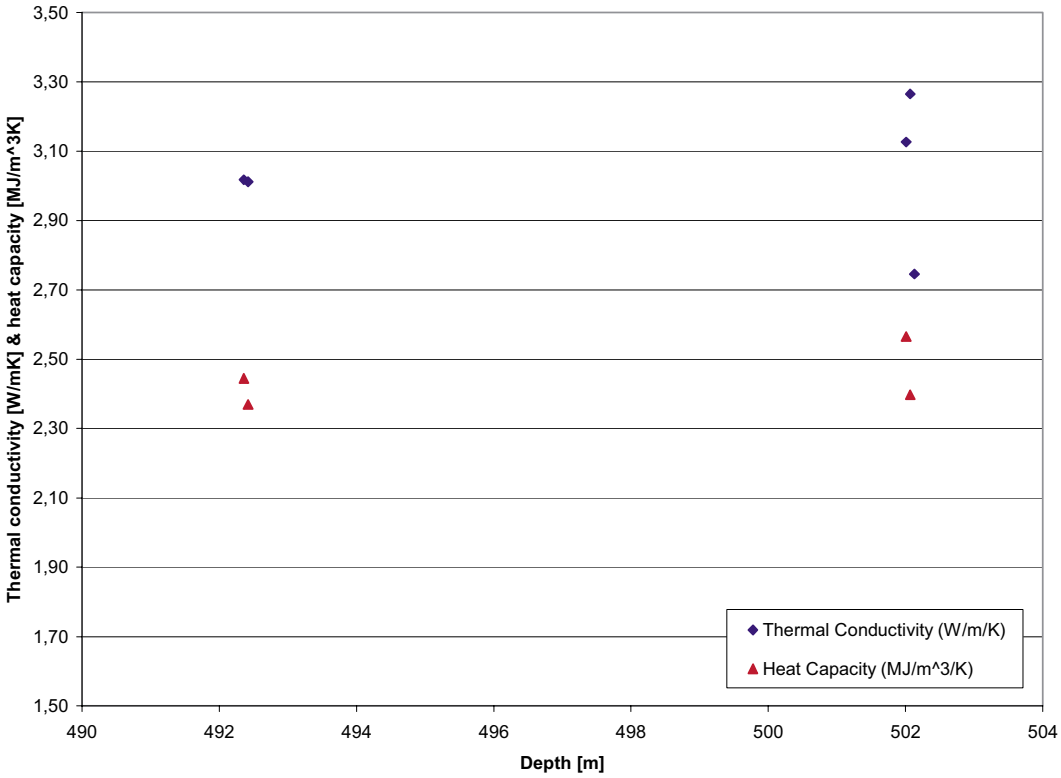

Figure 5-17. *Thermal conductivity and heat capacity at different depth at 50°C.*

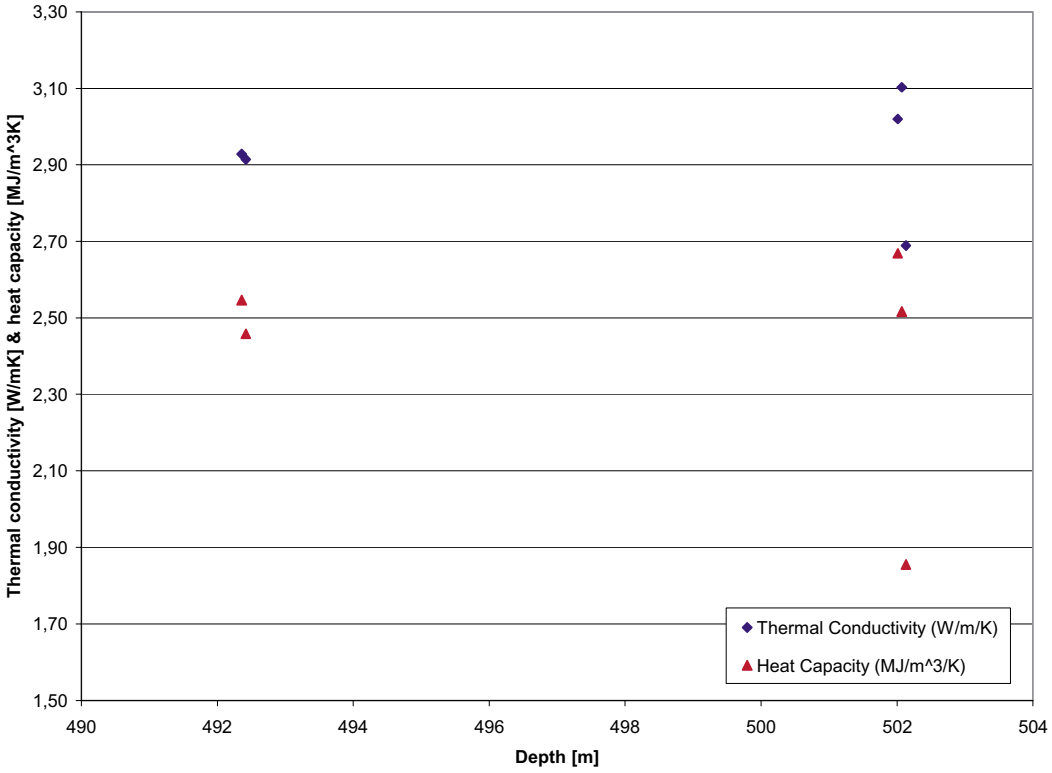

Figure 5-18. *Thermal conductivity and heat capacity at different depth at 80°C.*

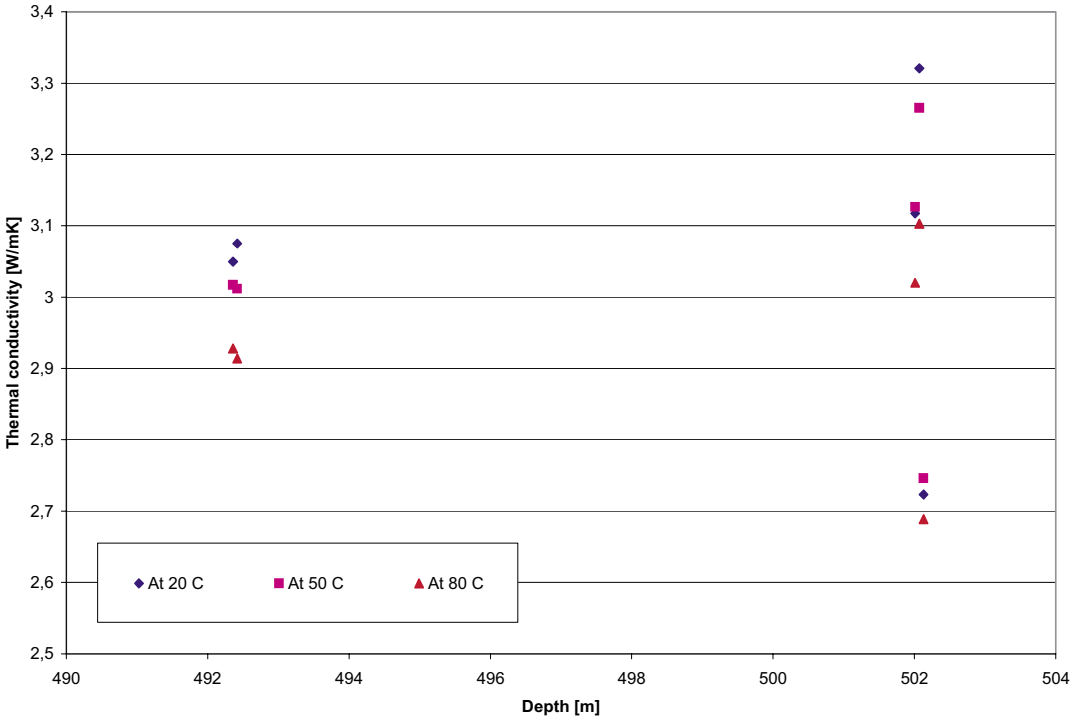

Figure 5-19. *Thermal conductivity at different depth and at different temperatures.*

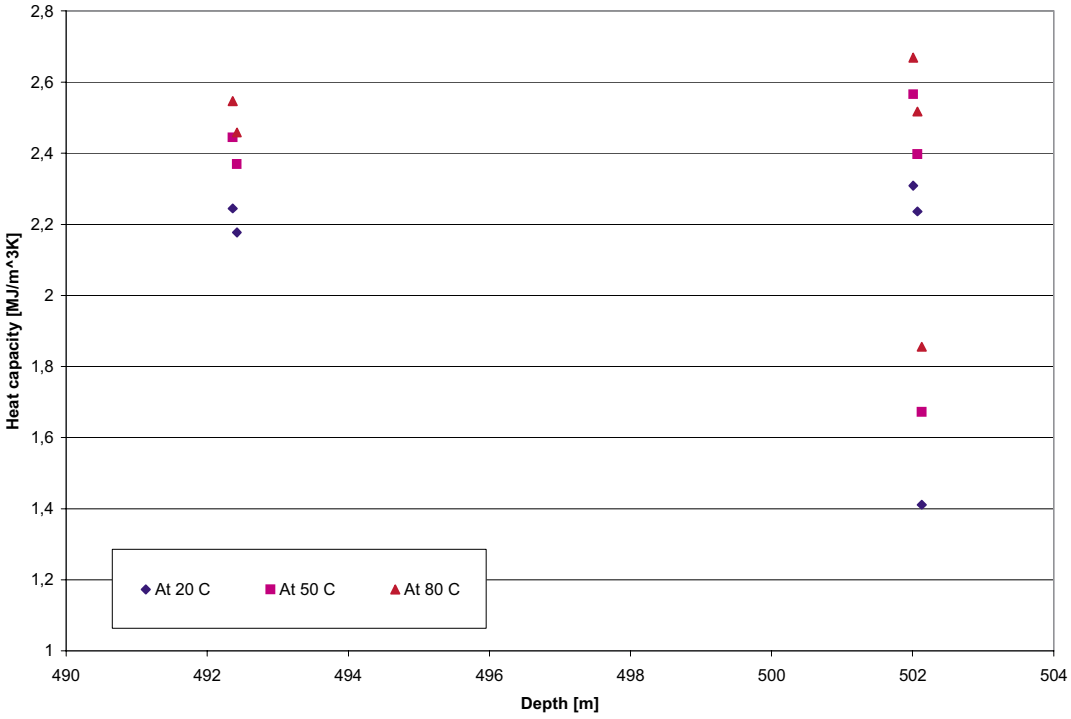

Figure 5-20. *Heat capacity at different depth and at different temperatures.*

Maximum variation of thermal conductivity in the temperature range 20 ºC to 80 ºC was 6% for sample X02-90V-8 and maximum variation of heat capacity in the same temperature range was about 32% for sample X02-90V-11.

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.

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 Apatite and Prehnite.

Table 5-37. Mineralogical composition (in vol %) of the investigated specimens from KLX02, 500 points are counted on each specimen.

Identification	Sampling depth (Sec low)	Qtz	Kfs	Pl	Bt	Sph	Op	As	Am	Ep
KLX02A-200-1	314.65	23	25	37	11	0.6	0.6	–	–	2
KLX02A-200-2	320.88	21	34	34	8	0.6	1	–	–	1
KLX02A-200-3	492.3	24	19	47	7	0.8	0.2	0.2	–	2
KLX02A-200-4	502.21	26	25	39	8	1	0.6	0.2	–	1
KLX02A-200-5	738.36	25	19	45	8	0.4	0.6	0.2	–	3
KLX02A-200-6	740.28	26	25	41	6	0.8	0.2	0.8	–	0.8

5.3 Discussion

There were no deviations to 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 1.5
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 (mm^2/s)	Heat capacity ($MJ/(m^3, K)$)
X02-90V-01			
1	3.21	1.45	2.22
2	3.22	1.44	2.23
3	3.22	1.44	2.24
4	3.22	1.44	2.24
5	3.20	1.46	2.20
X02-90V-02			
1	3.27	1.34	2.44
2	3.28	1.33	2.47
3	3.28	1.33	2.48
4	3.28	1.34	2.45
5	3.27	1.34	2.44
X02-90V-03			
1	3.09	1.32	2.35
2	3.10	1.31	2.37
3	3.09	1.32	2.34
4	3.09	1.32	2.34
5	3.09	1.31	2.35
X02-90V-04			
1	3.13	1.37	2.28
2	3.13	1.37	2.28
3	3.13	1.38	2.27
4	3.11	1.39	2.24
5	3.12	1.39	2.24
X02-90V-05			
1	3.07	1.38	2.23
2	3.07	1.38	2.23
3	3.07	1.38	2.22
4	3.07	1.38	2.23
5	3.07	1.38	2.22
X02-90V-07			
1	3.05	1.36	2.24
2	3.05	1.36	2.25
3	3.05	1.36	2.25
4	3.05	1.36	2.24
5	3.05	1.35	2.25
X02-90V-08			
1	3.07	1.42	2.17
2	3.08	1.41	2.18
3	3.08	1.41	2.18
4	3.08	1.41	2.18
5	3.08	1.41	2.18

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

Measurement number	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity ($MJ/(m^3, K)$)
X02-90V-09			
1	3.11	1.35	2.31
2	3.12	1.35	2.31
3	3.12	1.35	2.31
4	3.12	1.35	2.31
5	3.12	1.35	2.30
X02-90V-10			
1	3.32	1.49	2.23
2	3.32	1.49	2.23
3	3.32	1.49	2.24
4	3.33	1.48	2.24
5	3.32	1.48	2.24
X02-90V-11			
1	2.74	1.93	1.41
2	2.71	1.94	1.40
3	2.72	1.93	1.40
4	2.72	1.93	1.41
5	2.73	1.90	1.43
X02-90V-13			
1	3.25	1.33	2.45
2	3.25	1.32	2.47
3	3.25	1.31	2.48
4	3.25	1.31	2.48
5	3.25	1.31	2.49
X02-90V-14			
1	3.11	1.49	2.08
2	3.10	1.50	2.07
3	3.10	1.50	2.07
4	3.09	1.49	2.07
5	3.09	1.50	2.06
X02-90V-15			
1	3.06	1.53	2.00
2	3.05	1.54	1.99
3	3.05	1.53	1.99
4	3.05	1.53	1.99
5	3.03	1.56	1.94
X02-90V-16			
1	3.03	1.34	2.26
2	3.04	1.33	2.29
3	3.04	1.32	2.29
4	3.03	1.33	2.28
5	3.03	1.32	2.29
X02-90V-17			
1	3.10	1.31	2.37
2	3.11	1.31	2.37
3	3.10	1.31	2.36
4	3.09	1.30	2.37
5	3.08	1.30	2.37

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

Measurement number	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity ($MJ/(m^3, K)$)
X02-90V-07			
1	3.02	1.23	2.45
2	3.02	1.23	2.46
3	3.02	1.24	2.43
4	3.02	1.24	2.44
5	3.01	1.23	2.44
F01A-90V-08			
1	3.01	1.27	2.37
2	3.01	1.27	2.37
3	3.02	1.27	2.37
4	3.01	1.27	2.36
5	3.01	1.27	2.37
X02-90V-09			
1	3.12	1.21	2.58
2	3.13	1.22	2.57
3	3.13	1.22	2.56
4	3.13	1.22	2.56
5	3.12	1.22	2.56
X02-90V-10			
1	3.26	1.37	2.39
2	3.27	1.36	2.40
3	3.27	1.36	2.40
4	3.27	1.37	2.39
5	3.26	1.35	2.41
X02-90V-11			
1	2.75	1.62	1.70
2	2.75	1.64	1.68
3	2.74	1.65	1.66
4	2.74	1.65	1.66
5	2.74	1.65	1.67

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

Measurement number	Conductivity (W/(m, K))	Diffusivity (mm^2/s)	Heat capacity ($MJ/(m^3, K)$)
X02-90V-07			
1	2.93	1.15	2.56
2	2.93	1.15	2.55
3	2.93	1.15	2.55
4	2.92	1.16	2.51
5	2.93	1.14	2.56
F01A-90V-08			
1	2.92	1.19	2.46
2	2.92	1.19	2.46
3	2.91	1.19	2.45
4	2.91	1.19	2.45
5	2.91	1.18	2.48
X02-90V-09			
1	3.02	1.13	2.67
2	3.03	1.13	2.68
3	3.01	1.13	2.66
4	3.02	1.13	2.68
5	3.02	1.14	2.65
X02-90V-10			
1	3.10	1.23	2.52
2	3.11	1.23	2.52
3	3.11	1.23	2.53
4	3.11	1.23	2.52
5	3.09	1.23	2.50
X02-90V-11			
1	2.69	1.45	1.86
2	2.69	1.46	1.84
3	2.69	1.45	1.85
4	2.69	1.45	1.85
5	2.69	1.43	1.88

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
X02-90V-01			
1	20	0.70	72–200
2	20	0.70	74–200
3	20	0.70	75–200
4	20	0.70	76–200
5	20	0.71	74–200
X02-90V-02			
1	20	0.65	69–200
2	20	0.64	71–200
3	20	0.64	73–200
4	20	0.65	68–200
5	20	0.65	69–200
X02-90V-03			
1	20	0.64	52–200
2	20	0.63	49–200
3	20	0.64	43–200
4	20	0.64	46–200
5	20	0.64	45–200
X02-90V-04			
1	20	0.67	68–200
2	20	0.67	56–200
3	20	0.67	55–200
4	20	0.68	53–200
5	20	0.68	55–200
X02-90V-05			
1	20	0.67	87–200
2	20	0.67	87–200
3	20	0.67	85–200
4	20	0.67	85–200
5	20	0.67	85–200
X02-90V-07			
1	20	0.66	28–200
2	20	0.66	31–200
3	20	0.66	29–200
4	20	0.66	30–200
5	20	0.66	25–200
X02-90V-08			
1	20	0.69	20–200
2	20	0.68	10–200
3	20	0.68	15–200
4	20	0.69	12–200
5	20	0.68	12–200

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
X02-90V-09			
1	20	0.65	48–200
2	20	0.66	45–200
3	20	0.65	45–200
4	20	0.65	48–200
5	20	0.66	37–200
X02-90V-10			
1	20	0.72	54–200
2	20	0.72	52–200
3	20	0.72	53–200
4	20	0.72	58–200
5	20	0.72	54–200
X02-90V-11			
1	20	0.94	104–200
2	20	0.94	103–200
3	20	0.94	104–200
4	20	0.94	105–200
5	20	0.92	103–200
X02-90V-13			
1	20	0.64	62–200
2	20	0.64	52–200
3	20	0.63	44–199
4	20	0.64	53–200
5	20	0.63	53–200
X02-90V-14			
1	20	0.73	33–200
2	20	0.73	42–200
3	20	0.73	24–200
4	20	0.72	24–200
5	20	0.73	27–200
X02-90V-15			
1	20	0.74	46–200
2	20	0.75	44–200
3	20	0.74	41–200
4	20	0.74	45–200
5	20	0.76	49–200
X02-90V-16			
1	20	0.65	64–200
2	20	0.64	56–200
3	20	0.64	65–200
4	20	0.64	57–200
5	20	0.64	65–200
X02-90V-17			
1	20	0.64	67–200
2	20	0.64	68–200
3	20	0.64	65–200
4	20	0.63	68–200
5	20	0.63	70–200

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
X02-90V-07			
1	20	0.60	27–200
2	20	0.60	25–200
3	20	0.60	26–200
4	20	0.60	29–200
5	20	0.60	27–200
F01A-90V-08			
1	20	0.62	17–200
2	20	0.62	15–200
3	20	0.62	14–200
4	20	0.62	10–200
5	20	0.62	12–200
X02-90V-09			
1	20	0.59	41–200
2	20	0.59	35–200
3	20	0.59	20–200
4	20	0.59	25–200
5	20	0.59	24–198
X02-90V-10			
1	20	0.66	43–200
2	20	0.66	41–200
3	20	0.66	38–200
4	20	0.66	32–200
5	20	0.66	45–200
X02-90V-11			
1	20	0.79	99–200
2	20	0.80	97–200
3	20	0.80	101–200
4	20	0.80	99–200
5	20	0.80	98–200

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
X02-90V-07			
1	20	0.56	31–200
2	20	0.56	36–200
3	20	0.56	31–200
4	20	0.56	29–200
5	20	0.56	41–200
F01A-90V-08			
1	20	0.58	16–200
2	20	0.58	21–200
3	20	0.55	18–190
4	20	0.58	24–200
5	20	0.57	20–200
X02-90V-09			
1	20	0.55	39–200
2	20	0.55	83–200
3	20	0.55	71–200
4	20	0.55	24–200
5	20	0.55	33–200
X02-90V-10			
1	20	0.60	22–200
2	20	0.60	39–200
3	20	0.60	30–200
4	20	0.60	30–200
5	20	0.60	31–200
X02-90V-11			
1	20	0.70	96–200
2	20	0.71	99–200
3	20	0.70	97–200
4	20	0.70	97–200
5	20	0.70	98–200