P-04-161

Forsmark site investigation

Drill hole KFM02A

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

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December 2004

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Abstract

Thermal properties on fifteen specimens from drill hole KFM02A, Forsmark, Sweden, were measured at ambient and elevated temperature. The rock type of all samples is medium-grained metagranite (-granodiorite). The mineralogical content was determined by using modal analysis.

The determination of the thermal properties is 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 larger than on the conductivity. Thermal conductivity and thermal diffusivity of specimens at different depths at 20°C were in the range of 3.49–4.01 W/(m, K) and 1.58–2.05 mm^2/s respectively. At 80°C, thermal conductivity and thermal diffusivity of specimens were in the range of 3.35–3.73 W/(m, K) and 1.28–1.51 mm^2/s respectively.

Contents

1 Introduction

The objective of this investigation was to determine thermal properties of drill core specimens borehole KFM02A, Forsmark, Sweden, 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 followed the activity plan AP PF 400-04-19 (SKB internal controlling document) and was controlled by SP-QD 13.1 (SP quality document).

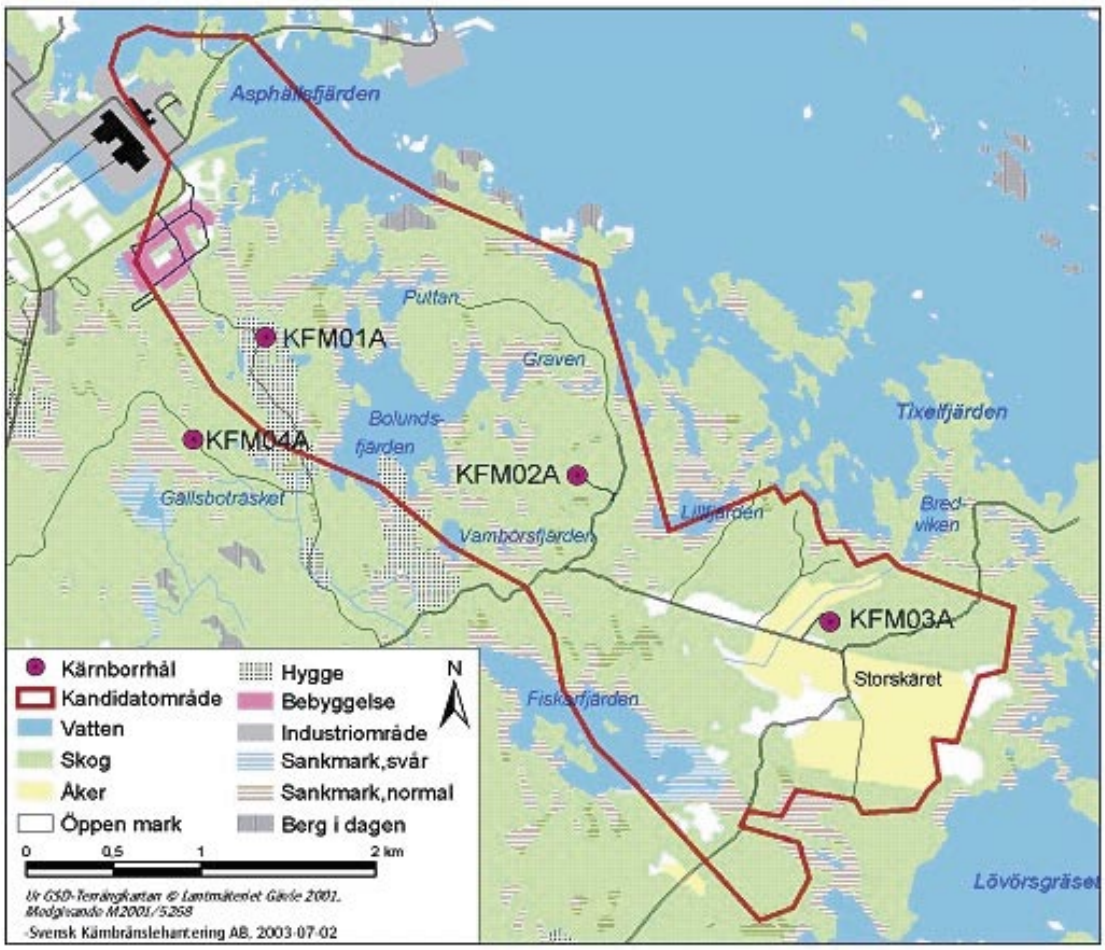

Figure 1-1. *Location of drill hole KFM02A at the Forsmark site.*

The samples were water saturated and stored in this condition for 7 days. This yielded 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 at SP in June 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 SP Fire Technology. Density was determined in compliance with SKB MD 160.002, version 1.9 (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 Forsmark.

The samples derive from borehole KFM02A in Forsmark, which is a semi-vertical telescopic borehole of SKB-chemistry type with a drilling length of c 1,000 m. The specimens were sampled on three levels in the drill hole: c 335 m, 530 m, and 710 m. The investigated rock type is mapped as medium-grained metagranite (-granodiorite) (rock code 101057).

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 1-1.
- 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).

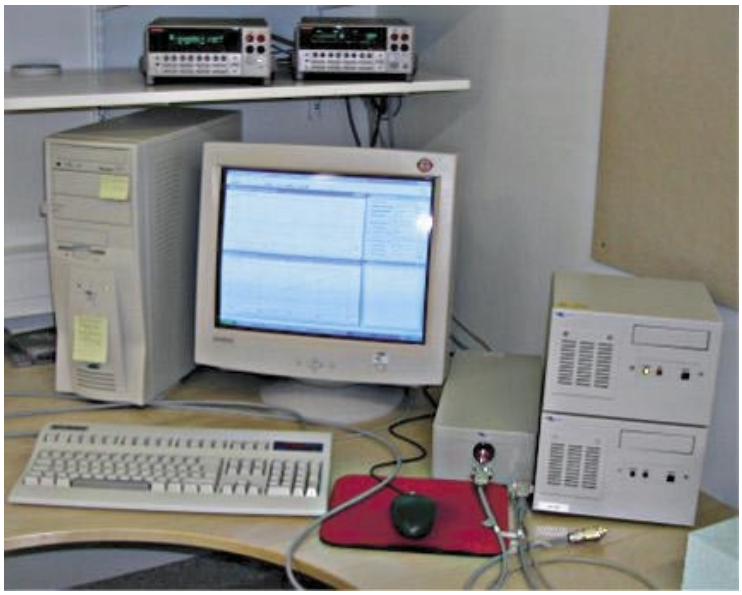

Figure 3-1. *TPS-apparatus with source meter, multi-meter, bridge, and computer.*

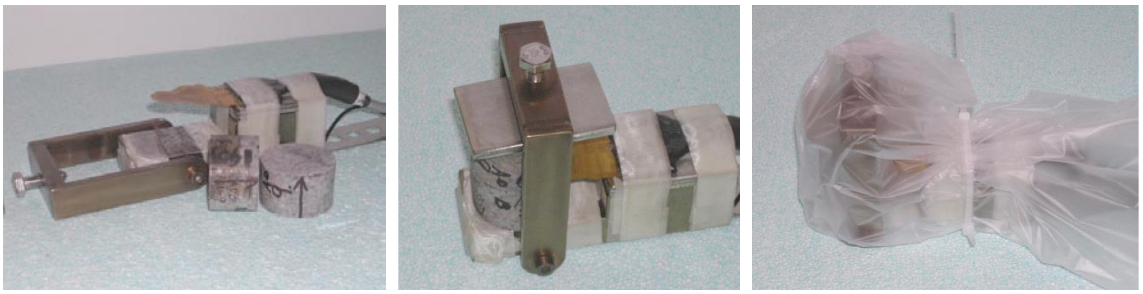

Figure 3-2. *Specimens prior to mounting (left), mounted in stainless sample holder (middle), and sample holder with mounted specimens wrapped in plastic (right).*

4 Execution

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

Density was determined in compliance with SKB MD 160.002, version 1.9 (SKB internal controlling document), and ISRM /3/. Modal analysis was determined in according to SKB MD 160.001, version 1.9, (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 KFM02A. The first level was between 330 m and 337 m, the second between 528 m and 537 m, and the third level between 705 m and 720 m. The thirty specimens, with a thickness of 25 mm each, were prepared 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 KFM02A within the SICADA database at SKB.

Each sample is assigned an identification number composed of the combination KFM02A-90V (in some figures abbreviated F02A-90), followed by the serial numbers -1, -2, -3 etc for thermal properties, respectively KFM02A-200, followed by serial numbers for modal analysis.

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

Identification	Rock type	Sampling depth (Sec low)
KFM02A-90V-1	Metagranite	330.60
KFM02A-90V-2	Metagranite	336.11
KFM02A-90V-3	Metagranite	336.68
KFM02A-90V-4	Metagranite	336.87
KFM02A-90V-5	Metagranite	336.99
KFM02A-90V-7	Metagranite	528.27
KFM02A-90V-8	Metagranite	530.88
KFM02A-90V-9	Metagranite	531.01
KFM02A-90V-10	Metagranite	532.21
KFM02A-90V-11	Metagranite	536.69
KFM02A-90V-13	Metagranite	704.56
KFM02A-90V-14	Metagranite	706.38
KFM02A-90V-15	Metagranite	706.70
KFM02A-90V-16	Metagranite	718.34
KFM02A-90V-17	Metagranite	719.41

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 temperature (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 then 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 carried out during March–May 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 SP Building Technology and Mechanics.

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 1.1.1 and in the SICADA database at SKB under field note no Forsmark 142. 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 F02A-90V-01

Figure 5-1. *Specimens F02A-90V-01.*

Table 5-1. Porosity, wet and dry density of specimens F02A-90V-01, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
F02A-90V-01			
Sec low: 330.60	2,657	2,654	0.31

Table 5-2. Thermal properties of sample F02A-90V-01 at ambient temperature.

F02A-90V-01 Sec low: 330.60	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³· K)]
	20°C		
Mean value	3.49	1.75	2.00
Standard deviation	0.005	0.009	0.013

Sample F02A-90V-02

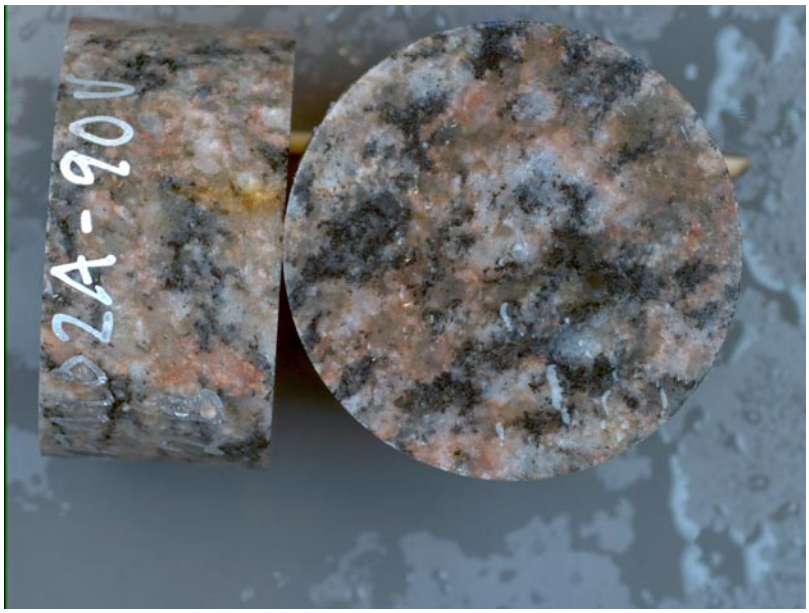

Figure 5-2. *Specimens F02A-90V-02.*

Table 5-3. Porosity, wet and dry density of specimens F02A-90V-02, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
F02A-90V-02			
Sec low: 336.11	2,655	2,653	0.26

Table 5-4. Thermal properties of sample F02A-90V-02 at ambient temperature.

F02A-90V-02 Sec low: 336.11	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]
	20°C		
Mean value	3.72	1.85	2.01
Standard deviation	0.002	0.008	0.009

Sample F02A-90V-03

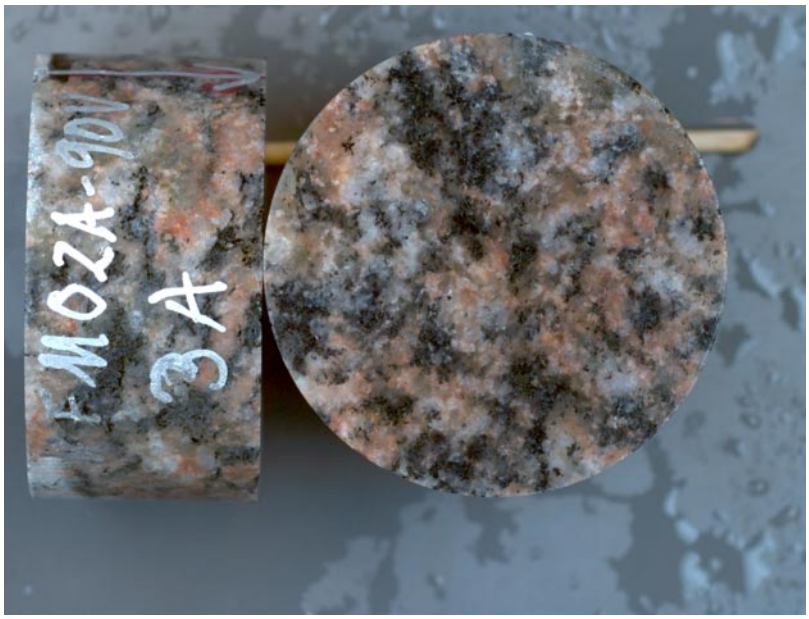

Figure 5-3. *Specimens F02A-90V-03.*

Table 5-5. Porosity, wet and dry density of specimens F02A-90V-03, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
F02A-90V-03			
Sec low: 336.68	2,650	2,648	0.24

Table 5-6. Thermal properties of sample F02A-90V-03 at ambient temperature.

F02A-90V-03 Sec low: 336.68	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.74	1.70	2.21
Standard deviation	0.002	0.007	0.010

Sample F02A-90V-04

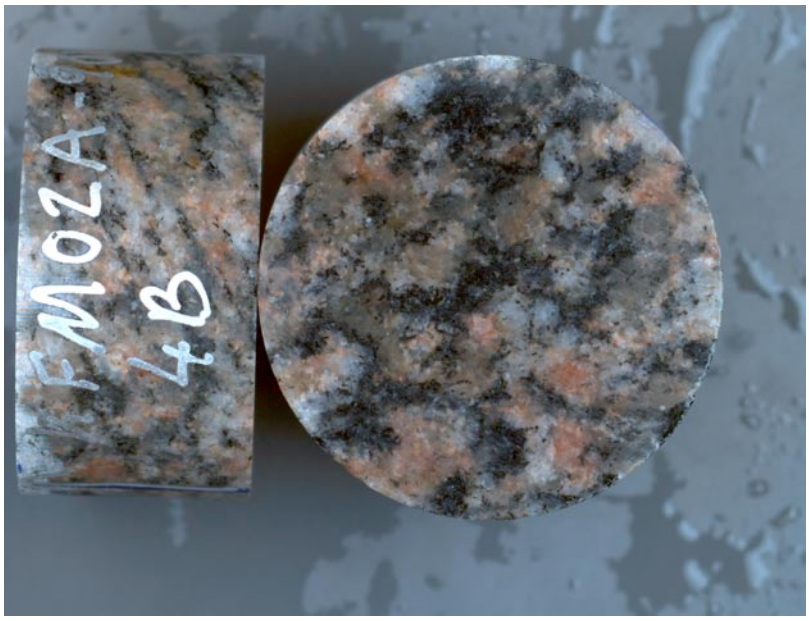

Figure 5-4. *Specimens F02A-90V-04.*

Table 5-7. Porosity, wet and dry density of specimens F02A-90V-04, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
F02A-90V-04			
Sec low: 336.87	2,659	2,656	0.28

Table 5-8. Thermal properties of sample F02A-90V-04 at ambient temperature.

F02A-90V-04 Sec low: 336.87	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]
	20°C		
Mean value	3.60	2.05	1.76
Standard deviation	0.003	0.004	0.004

Sample F02A-90V-05

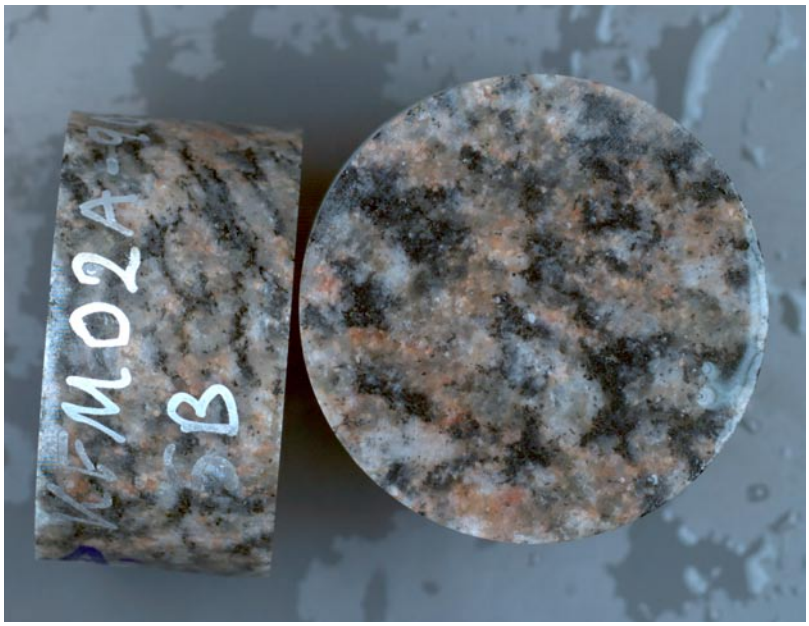

Figure 5-5. *Specimens F02A-90V-05.*

Table 5-9. Porosity, wet and dry density of specimens F02A-90V-05, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
F02A-90V-05			
Sec low: 336.99	2,662	2,658	0.42

Table 5-10. Thermal properties of sample F02A-90V-05 at ambient temperature.

F02A-90V-05 Sec low: 336.99	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.57	1.70	2.10
Standard deviation	0.009	0.010	0.016

Sample F02A-90V-07

Figure 5-6. *Specimens F02A-90V-07.*

Table 5-11. Porosity, wet and dry density of specimens F02A-90V-07, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
F02A-90V-07			
Sec low: 528.27	2,644	2,640	0.40

Table 5-12. Thermal properties of sample F02A-90V-07 at different temperatures.

F02A-90V-07 Sec low: 528.27	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]
	20°C		
Mean value	4.01	1.74	2.31
Standard deviation	0.004	0.005	0.008
	50°C		
Mean value	3.86	1.55	2.49
Standard deviation	0.005	0.006	0.012
	80°C		
Mean value	3.73	1.42	2.63
Standard deviation	0.003	0.008	0.016

Sample F02A-90V-08

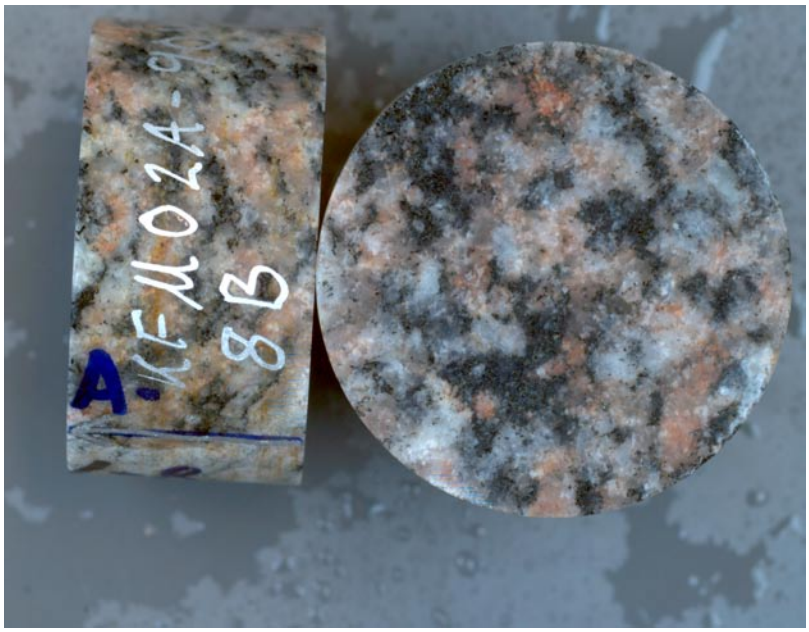

Figure 5-7. *Specimens F02A-90V-08.*

Table 5-13. Porosity, wet and dry density of specimens F02A-90V-08, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
F02A-90V-08			
Sec low: 530.88	2,660	2,656	0.34

Table 5-14. Thermal properties of sample F02A-90V-08 at different temperatures.

F02A-90V-08 Sec low: 530.88	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.70	1.76	2.11
Standard deviation	0.009	0.009	0.013
	50°C		
Mean value	3.58	1.58	2.26
Standard deviation	0.008	0.012	0.021
	80°C		
Mean value	3.43	1.46	2.36
Standard deviation	0.011	0.017	0.026

Sample F02A-90V-09

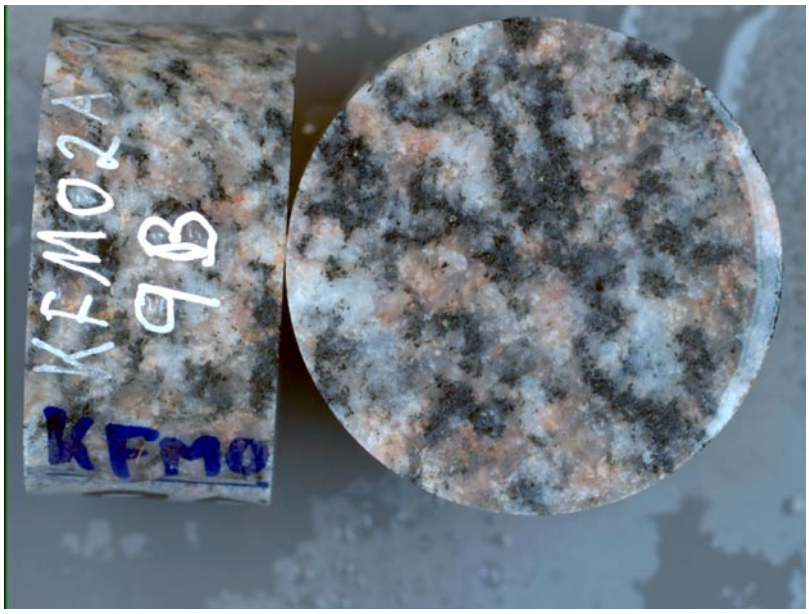

Figure 5-8. *Specimens F02A-90V-09.*

Table 5-15. Porosity, wet and dry density of specimens F02A-90V-09, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
F02A-90V-09			
Sec low: 531.01	2,658	2,654	0.40

Table 5-16. Thermal properties of sample F02A-90V-09 at different temperatures

F02A-90V-09 Sec low: 531.01	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.90	1.59	2.44
Standard deviation	0.004	0.008	0.011
	50°C		
Mean value	3.79	1.38	2.75
Standard deviation	0.006	0.003	0.006
	80°C		
Mean value	3.65	1.28	2.85
Standard deviation	0.005	0.003	0.006

Sample F02A-90V-10

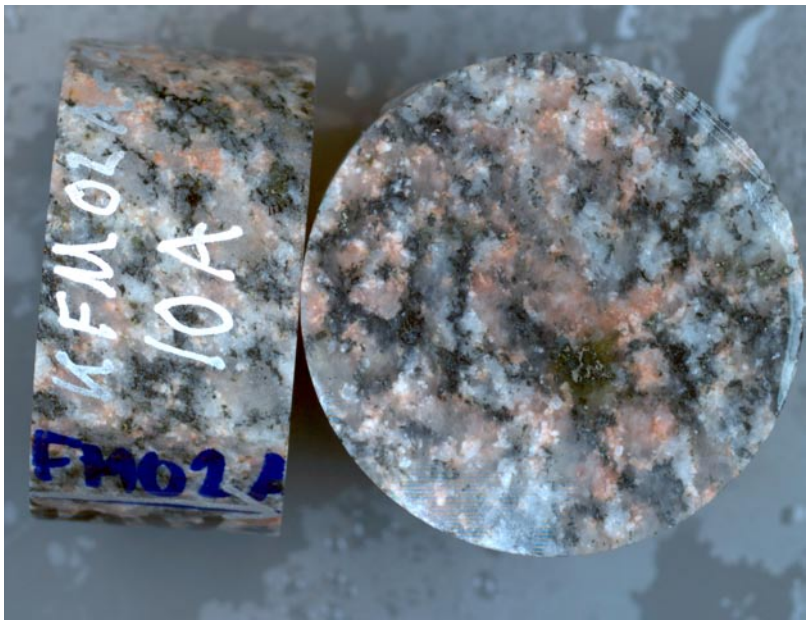

Figure 5-9. *Specimens F02A-90V-10.*

Table 5-17. Porosity, wet and dry density of specimens F02A-90V-10, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
F02A-90V-10			
Sec low: 532.21	2,652	2,649	0.35

Table 5-18. Thermal properties of sample F02A-90V-10 at different temperatures.

F02A-90V-10 Sec low: 532.21	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.55	1.62	2.19
Standard deviation	0.006	0.013	0.020
	50°C		
Mean value	3.53	1.40	2.53
Standard deviation	0.004	0.010	0.021
	80°C		
Mean value	3.35	1.30	2.58
Standard deviation	0.004	0.008	0.016

Sample F02A-90V-11

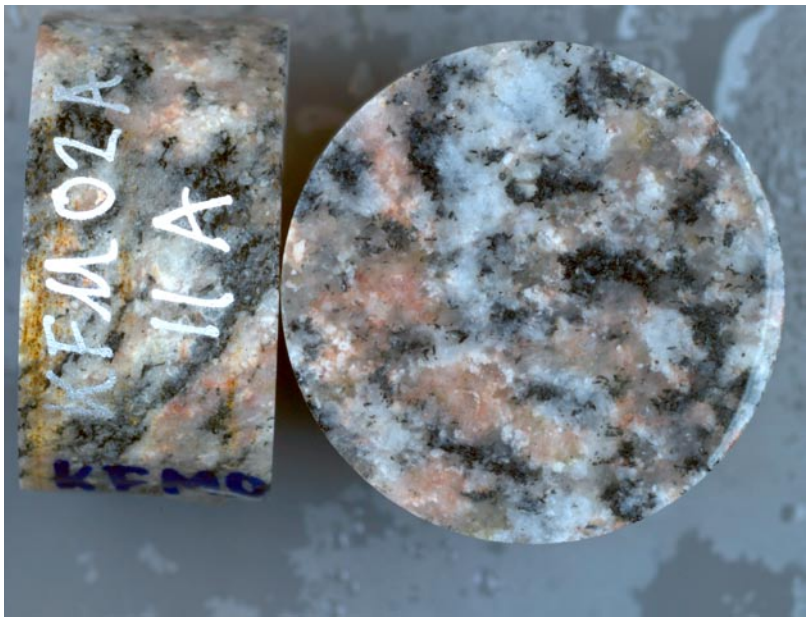

Figure 5-10. *Specimens F02A-90V-11.*

Table 5-19. Porosity, wet and dry density of specimens F02A-90V-11, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
F02A-90V-11			
Sec low: 536.69	2,650	2,647	0.29

Table 5-20. Thermal properties of sample F02A-90V-11 at different temperatures.

F02A-90V-11 Sec low: 536.69	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.66	1.80	2.03
Standard deviation	0.006	0.012	0.016
	50°C		
Mean value	3.57	1.63	2.19
Standard deviation	0.003	0.002	0.002
	80°C		
Mean value	3.44	1.51	2.28
Standard deviation	0.001	0.003	0.004

Sample F02A-90V-13

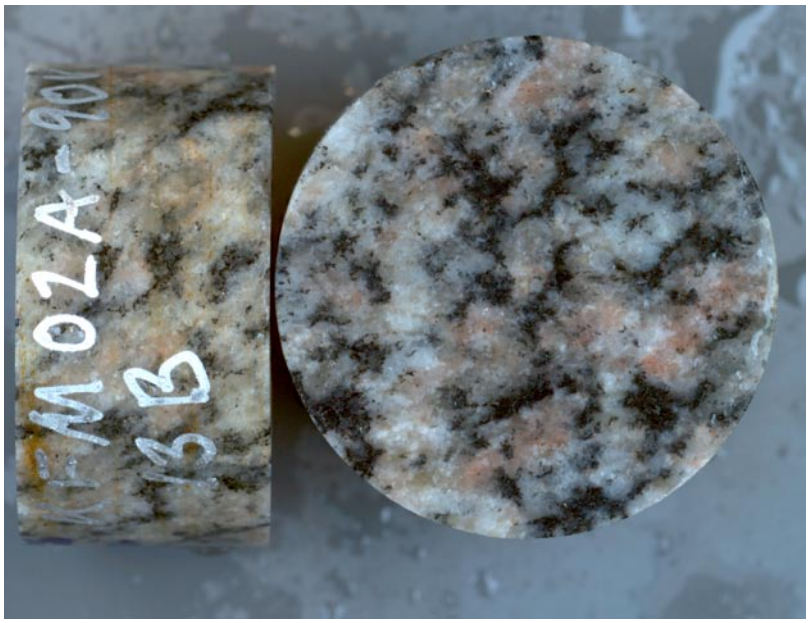

Figure 5-11. *Specimens F02A-90V-13.*

Table 5-21. Porosity, wet and dry density of specimens F02A-90V-13, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
F02A-90V-13			
Sec low: 704.56	2,656	2,653	0.25

Table 5-22. Thermal properties of sample F02A-90V-13 at ambient temperature.

F02A-90V-13 Sec low: 704.56	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.59	1.69	2.12
Standard deviation	0.006	0.004	0.006

Sample F02A-90V-14

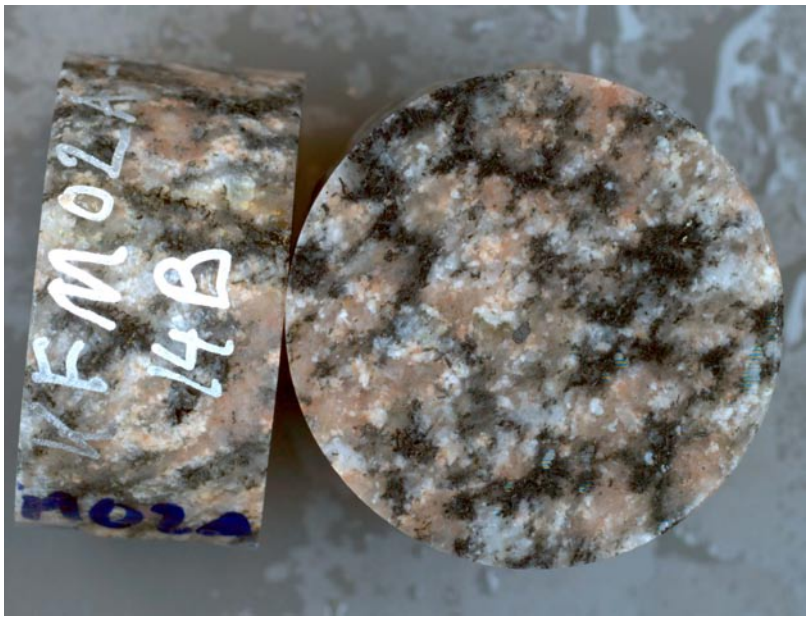

Figure 5-12. *Specimens F02A-90V-14.*

Table 5-23. Porosity, wet and dry density of specimens F02A-90V-14, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
F02A-90V-14			
Sec low: 706.38	2,657	2,654	0.30

Table 5-24. Thermal properties of sample F02A-90V-14 at ambient temperature.

F02A-90V-14 Sec low: 706.38	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	4.01	1.75	2.29
Standard deviation	0.004	0.003	0.005

Sample F02A-90V-15

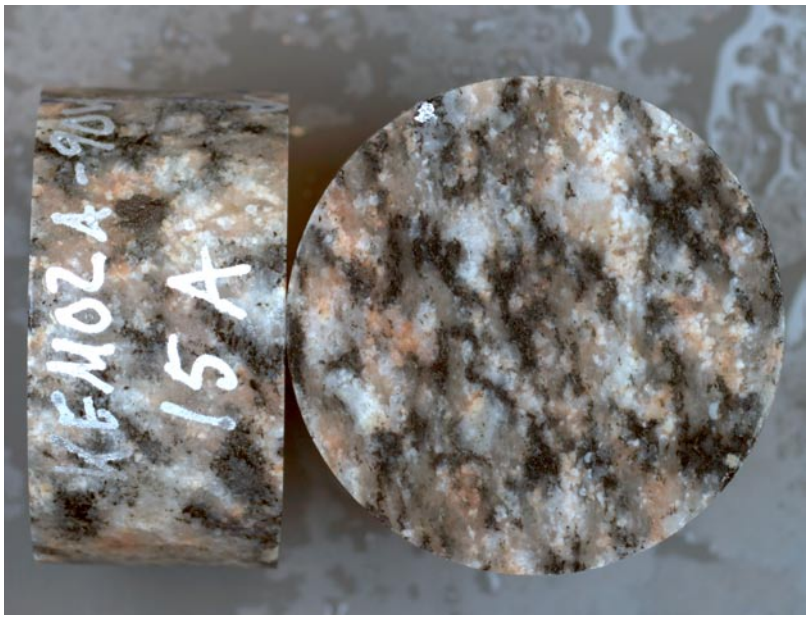

Figure 5-13. *Specimens F02A-90V-15.*

Table 5-25. Porosity, wet and dry density of specimens F02A-90V-15, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
F02A-90V-15			
Sec low: 706.70	2,660	2,657	0.34

Table 5-26. Thermal properties of sample F02A-90V-15 at ambient temperature.

F02A-90V-15 Sec low: 706.70	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	3.87	1.82	2.12
Standard deviation	0.007	0.005	0.007

Sample F02A-90V-16

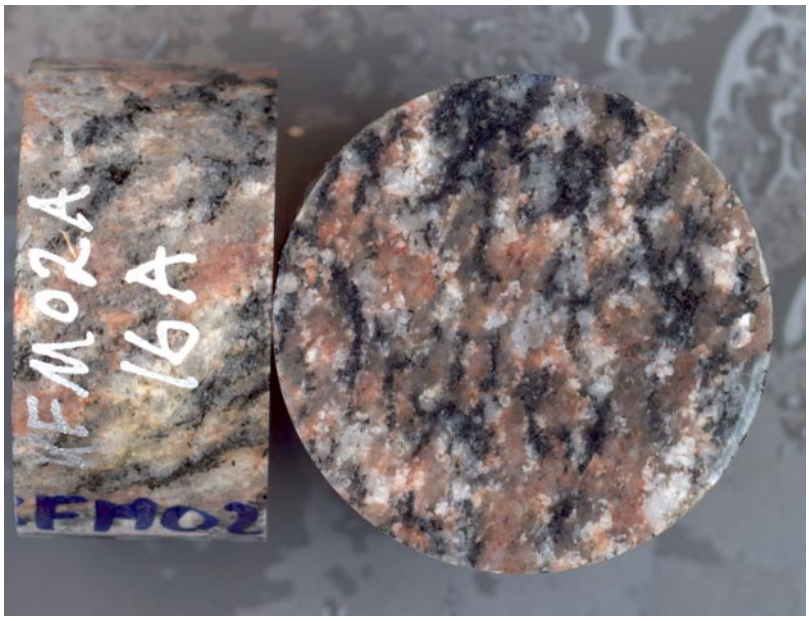

Figure 5-14. *Specimens F02A-90V-16.*

Table 5-27. Porosity, wet and dry density of specimens F02A-90V-16, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
F02A-90V-16			
Sec low: 718.34	2,654	2,651	0.29

Table 5-28. Thermal properties of sample F02A-90V-16 at ambient temperature.

F02A-90V-16 Sec low: 718.34	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
	20°C		
Mean value	4.00	1.65	2.42
Standard deviation	0.005	0.004	0.005

Sample F02A-90V-17

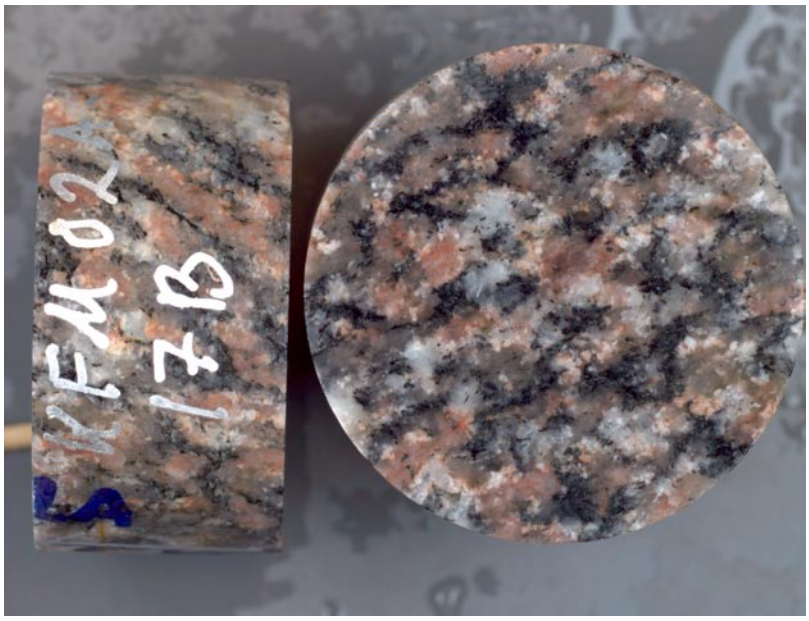

Figure 5-15. *Specimens F02A-90V-17.*

Table 5-29. Porosity, wet and dry density of specimens F02A-90V-17, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
F02A-90V-17			
Sec low: 719.41	2,654	2,651	0.31

Table 5-30. Thermal properties of sample F02A-90V-17 at ambient temperature.

F02A-90V-17 Sec low: 719.41	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
		20°C	
Mean value	3.70	1.58	2.34
Standard deviation	0.004	0.008	0.012

5.1.2 Summary of results

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 presented in Table 5-34 to Table 5-36.

Thermal conductivity and thermal diffusivity of specimens at different depths at 20°C were in the range of 3.49–4.01 W/(m, K) and 1.58–2.05 mm^2/s respectively. At 50°C, thermal conductivity and thermal diffusivity of specimens at different depths were in the range of 3.53–3.86 W/(m, K) and 1.38–1.63 mm^2/s respectively and, finally, at 80°C, thermal conductivity and thermal diffusivity of specimens were in the range of 3.35–3.73 W/(m, K) and 1.28–1.51 mm^2/s respectively.

Table 5-31. Thermal properties with mean values of samples at 20°C.

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [$MJ/(m^3, K)$]
F02A-90V-01	3.49	1.75	2.00
F02A-90V-02	3.72	1.85	2.01
F02A-90V-03	3.74	1.70	2.21
F02A-90V-04	3.60	2.05	1.76
F02A-90V-05	3.57	1.70	2.10
Mean value, level 335	3.63	1.81	2.01
F02A-90V-07	4.01	1.74	2.31
F02A-90V-08	3.70	1.76	2.11
F02A-90V-09	3.90	1.59	2.44
F02A-90V-10	3.55	1.62	2.19
F02A-90V-11	3.66	1.80	2.03
Mean value, level 530	3.76	1.70	2.22
F02A-90V-13	3.59	1.69	2.12
F02A-90V-14	4.01	1.75	2.29
F02A-90V-15	3.87	1.82	2.12
F02A-90V-16	4.00	1.65	2.42
F02A-90V-17	3.70	1.58	2.34
Mean value, level 710	3.84	1.70	2.26

Table 5-32. Thermal properties with mean values of samples at 50°C.

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [$MJ/(m^3, K)$]
F02A-90V-07	3.86	1.55	2.49
F02A-90V-08	3.58	1.58	2.26
F02A-90V-09	3.79	1.38	2.75
F02A-90V-10	3.53	1.40	2.53
F02A-90V-11	3.57	1.63	2.19
Mean value, level 530	3.67	1.51	2.45

Table 5-33. Thermal properties with mean values of samples at 80°C.

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
F02A-90V-07	3.73	1.42	2.63
F02A-90V-08	3.43	1.46	2.36
F02A-90V-09	3.65	1.28	2.85
F02A-90V-10	3.35	1.30	2.58
F02A-90V-11	3.44	1.51	2.28
Mean value, level 530	3.52	1.39	2.54

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

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
F02A-90V-01	0.005	0.009	0.013
F02A-90V-02	0.002	0.008	0.009
F02A-90V-03	0.002	0.007	0.010
F02A-90V-04	0.003	0.004	0.004
F02A-90V-05	0.009	0.010	0.016
F02A-90V-07	0.004	0.005	0.008
F02A-90V-08	0.009	0.009	0.013
F02A-90V-09	0.004	0.008	0.011
F02A-90V-10	0.006	0.013	0.020
F02A-90V-11	0.006	0.012	0.016
F02A-90V-13	0.006	0.004	0.006
F02A-90V-14	0.004	0.003	0.005
F02A-90V-15	0.007	0.005	0.007
F02A-90V-16	0.005	0.004	0.005
F02A-90V-17	0.004	0.008	0.012

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

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
F02A-90V-07	0.005	0.006	0.012
F02A-90V-08	0.008	0.012	0.021
F02A-90V-09	0.006	0.003	0.006
F02A-90V-10	0.004	0.010	0.021
F02A-90V-11	0.003	0.002	0.002

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

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
F02A-90V-07	0.003	0.008	0.016
F02A-90V-08	0.011	0.017	0.026
F02A-90V-09	0.005	0.003	0.006
F02A-90V-10	0.004	0.008	0.016
F02A-90V-11	0.001	0.003	0.004

5.1.3 Graphical presentation of results

Variations of the thermal conductivity and heat capacity in relation to sampling depth at different temperatures are shown in Figure 5-16 to Figure 5-20.

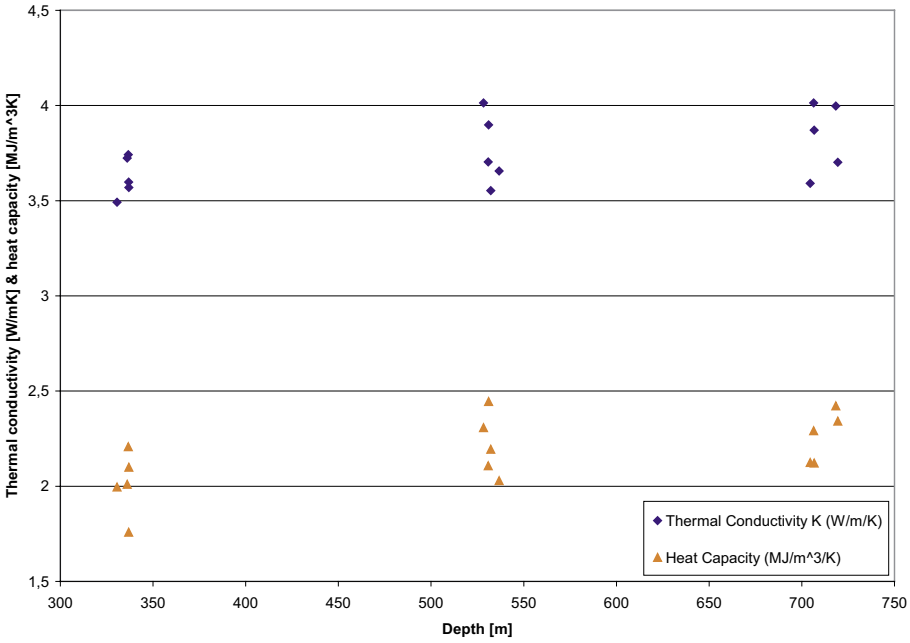

Figure 5-16. *Thermal conductivity and heat capacity at different depths at 20°C.*

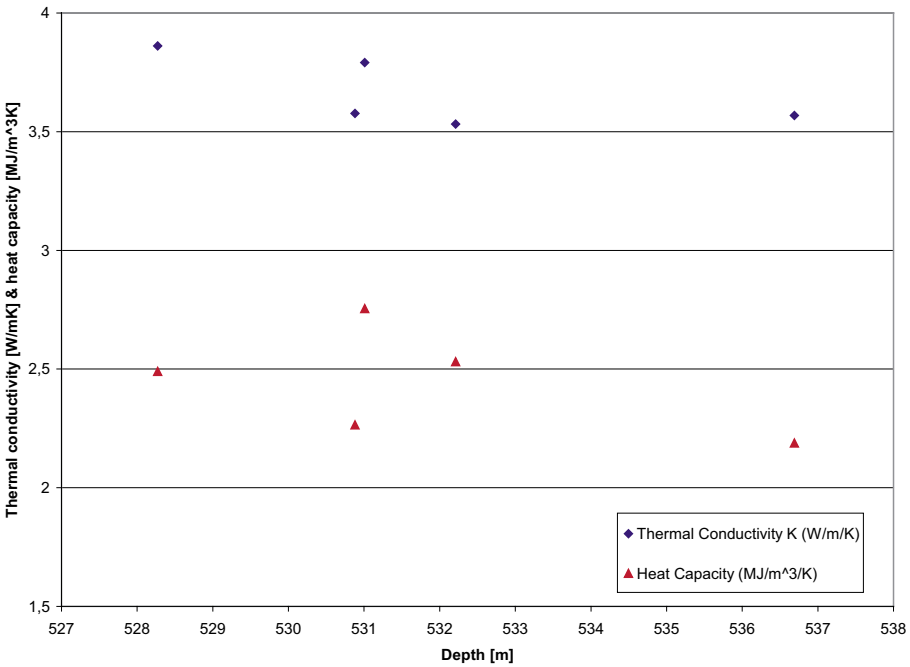

Figure 5-17. *Thermal conductivity and heat capacity at different depths at 50°C.*

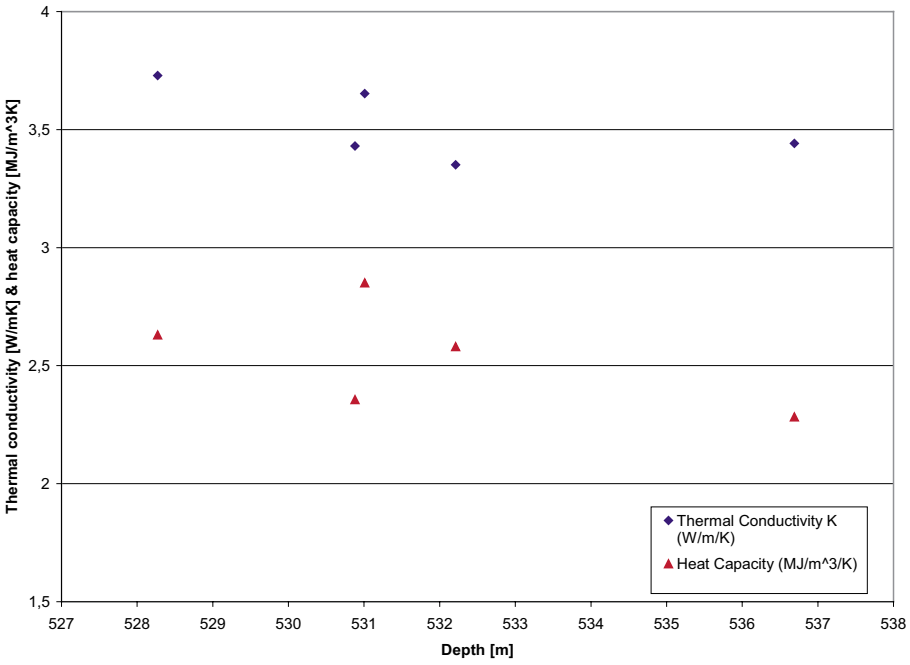

Figure 5-18. *Thermal conductivity and heat capacity at different depths at 80°C.*

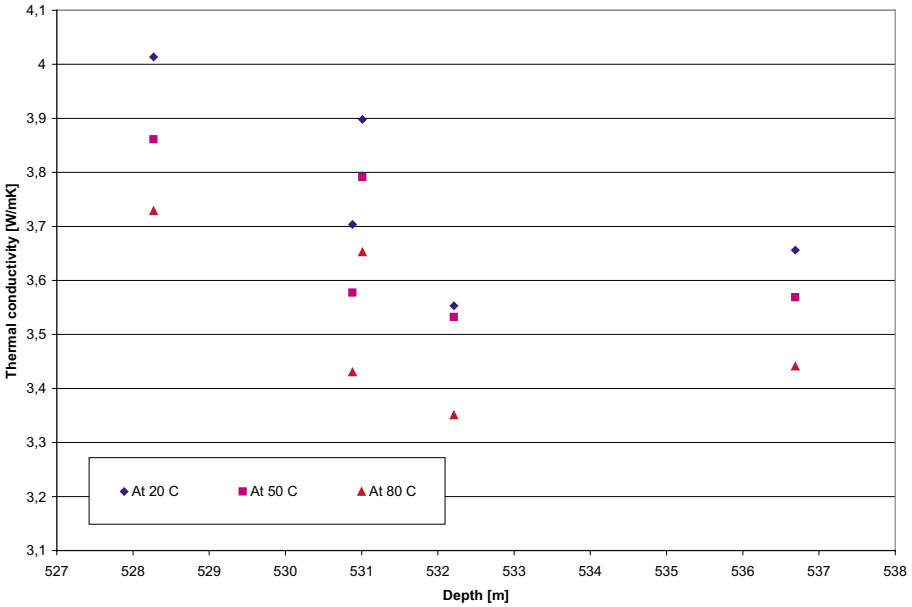

Figure 5-19. *Thermal conductivity at different depths and at different temperatures.*

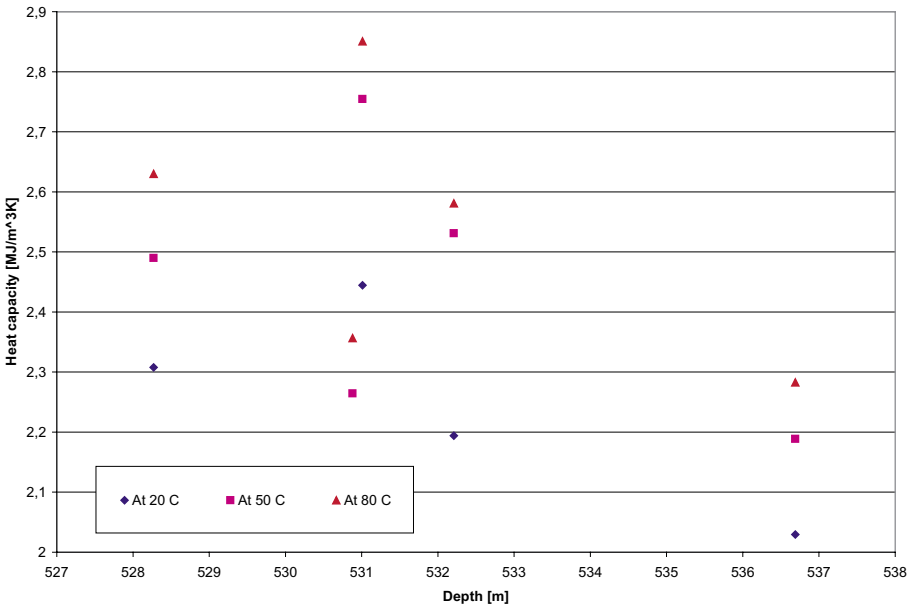

Figure 5-20. *Heat capacity at different depths and at different temperatures.*

The maximum variation of thermal conductivity in the temperature range 20°C to 80°C was 8% for sample F02A-90V-8 and the maximum variation of heat capacity in the same temperature range was about 15% for sample F02A-90V-10.

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 5-37 and Sec low in Table 1-1). The modal analyses were carried out 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 KFM02A, 500 points are counted on each specimen.

Identification	Sampling depth (Sec up)	Qtz	Kfs	Pl	Bt	Ch	Op	As
KFM02A-200-1	336.11	38	39	18	5	0	1	0
KFM02A-200-2	337.12	40	25	29	5	0	1	0.5
KFM02A-200-3	530.69	38	29	27	0	5	0.2	1
KFM02A-200-4	536.51	28	27	39	4	0	1	0
KFM02A-200-5	704.56	43	24	28	4	0	0.2	0.4
KFM02A-200-6	719.24	35	37	22	0	5	0	0.4

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, As = Accessory minerals.

5.3 Nonconformities

None.

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.

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 [mm²/s]	Heat capacity [MJ/(m³, K)]
F02A-90V-01			
1	3.49	1.75	1.99
2	3.49	1.76	1.99
3	3.49	1.76	1.99
4	3.49	1.75	2.00
5	3.50	1.74	2.02
F02A-90V-02			
1	3.72	1.85	2.01
2	3.73	1.84	2.02
3	3.72	1.86	2.00
4	3.72	1.86	2.00
5	3.72	1.85	2.02
F02A-90V-03			
1	3.74	1.71	2.19
2	3.74	1.70	2.20
3	3.74	1.69	2.21
4	3.74	1.69	2.22
5	3.74	1.69	2.22
F02A-90V-04			
1	3.60	2.05	1.76
2	3.60	2.04	1.77
3	3.60	2.05	1.75
4	3.60	2.05	1.76
5	3.59	2.04	1.76
F02A-90V-05			
1	3.56	1.72	2.07
2	3.57	1.70	2.11
3	3.57	1.69	2.11
4	3.58	1.69	2.12
5	3.57	1.70	2.10
F02A-90V-07			
1	4.01	1.74	2.30
2	4.01	1.75	2.30
3	4.02	1.74	2.31
4	4.02	1.73	2.32
5	4.01	1.74	2.30
F02A-90V-08			
1	3.71	1.77	2.10
2	3.71	1.76	2.11
3	3.71	1.74	2.13
4	3.70	1.76	2.10
5	3.69	1.76	2.10

Measurement number	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
F02A-90V-09			
1	3.90	1.59	2.46
2	3.90	1.61	2.43
3	3.90	1.60	2.44
4	3.89	1.59	2.45
5	3.90	1.59	2.45
F02A-90V-10			
1	3.55	1.64	2.16
2	3.56	1.62	2.20
3	3.55	1.61	2.20
4	3.56	1.61	2.21
5	3.55	1.62	2.19
F02A-90V-11			
1	3.66	1.81	2.01
2	3.66	1.80	2.04
3	3.65	1.81	2.01
4	3.66	1.79	2.05
5	3.65	1.79	2.04
F02A-90V-13			
1	3.60	1.69	2.13
2	3.60	1.69	2.12
3	3.59	1.69	2.13
4	3.59	1.69	2.13
5	3.58	1.69	2.11
F02A-90V-14			
1	4.01	1.76	2.28
2	4.02	1.75	2.30
3	4.01	1.75	2.29
4	4.01	1.75	2.29
5	4.02	1.75	2.29
F02A-90V-15			
1	3.86	1.83	2.11
2	3.87	1.82	2.12
3	3.88	1.83	2.12
4	3.87	1.82	2.13
5	3.87	1.83	2.12
F02A-90V-16			
1	4.00	1.66	2.42
2	4.00	1.65	2.42
3	4.00	1.65	2.42
4	3.99	1.65	2.42
5	3.99	1.64	2.43

Measurement number	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
F02A-90V-17			
1	3.70	1.59	2.32
2	3.71	1.58	2.35
3	3.70	1.58	2.35
4	3.70	1.58	2.35
5	3.70	1.58	2.35

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

Measurement number	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
F02A-90V-07			
1	3.87	1.54	2.50
2	3.86	1.55	2.49
3	3.86	1.55	2.49
4	3.86	1.55	2.49
5	3.85	1.56	2.47
F01A-90V-08			
1	3.59	1.56	2.30
2	3.58	1.58	2.27
3	3.58	1.59	2.25
4	3.57	1.59	2.25
5	3.57	1.59	2.25
F02A-90V-09			
1	3.80	1.38	2.75
2	3.80	1.38	2.76
3	3.79	1.38	2.75
4	3.78	1.38	2.75
5	3.79	1.37	2.76
F02A-90V-10			
1	3.54	1.38	2.56
2	3.53	1.40	2.52
3	3.53	1.40	2.53
4	3.53	1.39	2.53
5	3.53	1.41	2.51
F02A-90V-11			
1	3.57	1.63	2.19
2	3.57	1.63	2.19
3	3.57	1.63	2.19
4	3.56	1.63	2.19
5	3.57	1.63	2.19

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

Measurement number	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
F02A-90V-07			
1	3.73	1.40	2.66
2	3.73	1.42	2.61
3	3.73	1.42	2.62
4	3.73	1.42	2.63
5	3.73	1.42	2.62
F01A-90V-08			
1	3.44	1.45	2.38
2	3.44	1.47	2.35
3	3.42	1.48	2.32
4	3.43	1.45	2.37
5	3.42	1.44	2.38
F02A-90V-09			
1	3.66	1.28	2.85
2	3.66	1.28	2.85
3	3.65	1.28	2.86
4	3.65	1.28	2.84
5	3.65	1.28	2.85
F02A-90V-10			
1	3.35	1.28	2.61
2	3.35	1.30	2.58
3	3.36	1.30	2.58
4	3.35	1.30	2.57
5	3.35	1.30	2.56
F02A-90V-11			
1	3.44	1.51	2.29
2	3.44	1.51	2.28
3	3.44	1.51	2.28
4	3.44	1.51	2.29
5	3.44	1.51	2.28

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
F02A-90V-01			
1	20	0.85	63– 200
2	20	0.85	67– 200
3	20	0.85	68– 200
4	20	0.84	65– 199
5	20	0.84	64– 200
F02A-90V-02			
1	20	0.90	46– 200
2	20	0.90	40– 200
3	20	0.90	44– 200
4	20	0.90	48– 200
5	20	0.90	46– 200
F02A-90V-03			
1	20	0.83	61– 200
2	20	0.82	63– 200
3	20	0.82	59– 199
4	20	0.82	59– 200
5	20	0.82	63– 200
F02A-90V-04			
1	20	0.99	69– 200
2	20	0.99	64– 200
3	20	1.00	70– 200
4	20	0.99	70– 200
5	20	0.99	69– 200
F02A-90V-05			
1	20	0.83	65– 200
2	20	0.82	70– 200
3	20	0.82	62– 200
4	20	0.82	68– 200
5	20	0.83	68– 200
F02A-90V-07			
1	20	0.84	20– 200
2	20	0.85	20– 200
3	20	0.84	20– 200
4	20	0.84	20– 200
5	20	0.84	20– 200
F02A-90V-08			
1	20	0.86	20– 200
2	20	0.85	20– 200
3	20	0.85	20– 200
4	20	0.85	20– 200
5	20	0.85	20– 200

Measurement number	Total time (s)	Total/Char time	Points
F02A-90V-09			
1	20	0.77	53– 200
2	20	0.78	45– 200
3	20	0.77	43– 199
4	20	0.77	51– 200
5	20	0.77	52– 200
F02A-90V-10			
1	20	0.80	63– 200
2	20	0.78	34– 200
3	20	0.78	41– 200
4	20	0.78	43– 200
5	20	0.79	44– 200
F02A-90V-11			
1	20	0.88	51– 200
2	20	0.87	48– 200
3	20	0.88	58– 200
4	20	0.87	54– 200
5	20	0.87	47– 200
F02A-90V-13			
1	20	0.82	67– 200
2	20	0.82	75– 200
3	20	0.82	66– 200
4	20	0.82	65– 200
5	20	0.82	74– 200
F02A-90V-14			
1	20	0.85	73– 200
2	20	0.85	65– 200
3	20	0.84	70– 197
4	20	0.85	68– 200
5	20	0.85	64– 200
F02A-90V-15			
1	20	0.89	28– 200
2	20	0.89	29– 200
3	20	0.89	35– 200
4	20	0.88	32– 200
5	20	0.89	29– 200
F02A-90V-16			
1	20	0.80	54– 200
2	20	0.80	53– 200
3	20	0.80	44– 200
4	20	0.80	52– 200
5	20	0.80	45– 200

Measurement number	Total time (s)	Total/Char time	Points
F02A-90V-17			
1	20	0.77	22– 200
2	20	0.77	21– 200
3	20	0.77	23– 200
4	20	0.76	23– 200
5	20	0.76	25– 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
F02A-90V-07			
1	20	0.75	23– 200
2	20	0.75	22– 200
3	20	0.75	25– 200
4	20	0.75	27– 200
5	20	0.76	19– 200
F01A-90V-08			
1	20	0.76	22– 200
2	20	0.77	19– 200
3	20	0.77	20– 200
4	20	0.77	19– 200
5	20	0.77	19– 200
F02A-90V-09			
1	20	0.67	60– 200
2	20	0.67	58– 200
3	20	0.67	59– 200
4	20	0.67	60– 200
5	20	0.67	60– 200
F02A-90V-10			
1	20	0.67	28– 200
2	20	0.68	26– 200
3	20	0.68	23– 200
4	20	0.68	26– 200
5	20	0.68	21– 200
F02A-90V-11			
1	20	0.79	22– 200
2	20	0.79	22– 200
3	20	0.79	20– 200
4	20	0.79	31– 200
5	20	0.79	21– 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
F02A-90V-07			
1	20	0.68	20– 200
2	20	0.69	17– 200
3	20	0.69	17– 200
4	20	0.69	17– 200
5	20	0.69	21– 200
F01A-90V-08			
1	20	0.70	19– 200
2	20	0.71	34– 200
3	20	0.72	53– 200
4	20	0.70	23– 200
5	20	0.70	43– 200
F02A-90V-09			
1	20	0.61	52– 197
2	20	0.61	50– 195
3	20	0.62	52– 200
4	20	0.61	47– 195
5	20	0.61	54– 198
F02A-90V-10			
1	20	0.62	25– 198
2	20	0.63	22– 200
3	20	0.63	19– 200
4	20	0.63	20– 200
5	20	0.63	20– 200
F02A-90V-11			
1	20	0.73	44– 200
2	20	0.73	40– 200
3	20	0.73	49– 200
4	20	0.73	45– 200
5	20	0.73	48– 200