P-07-62

Oskarshamn site investigation

Borehole KLX03, KLX05, KLX07, KLX10 and KLX11A

Thermal properties of rocks using calorimeter and TPS method, and mineralogical composition by modal analysis

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February 2007

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Keywords: Thermal properties, Thermal conductivity, Thermal diffusivity, Heat capacity, Transient Plane Source method, Calorimeter, AP PS 400-06-141.

Abstract

Thermal properties on thirty-five specimens of drill holes KLX03, KLX05, KLX07, KLX10 and KLX11A, Oskarshamn, Sweden, were measured at ambient temperature (20°C). Selective rock samples were taken from earlier investigations in the mentioned drill holes. The samples were taken from the rock types Ävrö granite (501044), Quartz monzodiorite (501036), Diorite/gabbro (501033) and Fine-grained diorite/gabbro (505102). The determination of the thermal properties is based on a direct measurement method, the so called "Transient Plane Source Method" (TPS). The specific heat capacity of the samples was also measured by a calorimeter. The mineralogical content was determined by using modal analysis.

Thermal conductivity and thermal diffusivity measured by TPS at 20°C were in the range of 2.22–3.48 W /(m, K) respectively 0.97–1.64 mm^2/s. The heat capacity, which was calculated from the thermal conductivity and diffusivity, ranged between 1.87 and 2.56 MJ/(m^3, K).

The specific heat capacity that was measured by calorimetric method was in the range of 0.76–0.82 J/(g, K).

Sammanfattning

Termiska egenskaper hos trettifem provkroppar från borrhålen KLX03, KLX05, KLX07, KLX10 och KLX11A, Oskarshamn, bestämdes vid rumstemperatur (20°C). Selektiva bergartsprover hade tagits från tidigare undersökningar av de nämnda borrhålen. De undersökta bergarterna är karterade som Ävrö granit (501044), Kvarts monzodiorit (501036), Diorit/gabbro (501033) and finkornig diorit/gabbro (505102). TPS metoden, ”Transient Plane Source”, användes för bestämning av de termiska egenskaperna. Specifika värmekapaciteten bestämdes även med en kalorimeter. Det mineralogiska innehållet bestämdes med hjälp av modalanalys.

Den termiska konduktiviteten och den termiska diffusiviteten mätt med TPS vid 20°C uppgick till 2,22–3,48 W/(m, K) respektive 0,97–1,64 mm^2/s. Från värdena på dessa parametrar kunde den volymmetriska värmekapaciteten beräknas och befanns ligga i intervallet 1,87 till 2,56 $MJ/(m^3, K)$.

Den specifika värmekapaciteten, som bestämts med kalorimeter, uppgick till 0,76–0,82 J/(g, K).

Contents

1 Introduction

SKB is planning to build a final repository for nuclear waste in bedrock. A final repository for nuclear waste demands knowledge about thermal properties of the rock. Oskarshamn, Sweden, is one of the areas selected for site investigations. The activity presented in this report is part of the site investigation program at Oskarshamn /1/.

Several boreholes at Oskarshamn have previously been investigated with respect to the thermal properties. This report presents investigations of thermal properties of rock samples from boreholes KLX03, KLX05, KLX07, KLX10 and KLX11A at Oskarshamn. The location of the telescopic as well as the conventionally drilled core boreholes is shown in Figure 1-1. The thermal properties thermal conductivity and thermal diffusivity have been determined by using the Transient Plane Source Method (TPS), (Gustafsson, 1991) /2/. The method determines thermal conductivity and diffusivity of a material. The volumetric heat capacity can be calculated if the density is known. The dry and wet densities, as well as porosity of the samples, were determined within the scope of a parallel activity /3/. In addition, specific heat capacity of samples was measured by calorimetric method /4/.

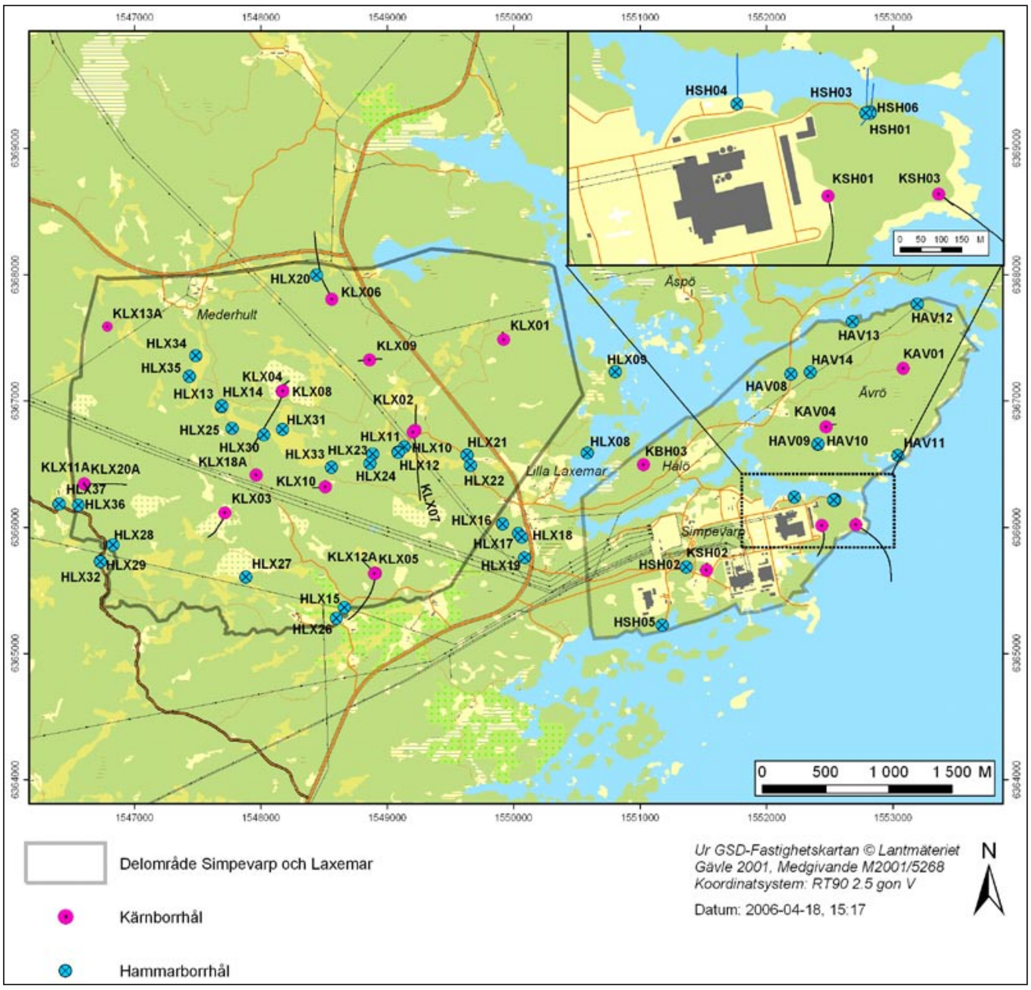

Figure 1-1. *Map over the Oskarshamn candidate area and cored boreholes.*

Modal analysis, based on point counting using a polarising microscope, was performed on ten specimens that were sampled quite close to ten specimens for thermal properties (TPS) (boreholes KLX05, KLX07, KLX10, and KLX11). The modal analysis was done in order to calculate the thermal properties based on the mineralogical composition of the specimens. The analysis was performed by Torbjörn Bergman, SGU. No description of the analysis is presented in this report, only the results.

Rock samples were selected at Oskarshamn based on the Boremap core logging with the strategy to investigate the properties of the dominant rock types as well as of a number of minority rock types.

The specimens to be tested were cut from the rock samples in the shape of circular discs. The rock samples arrived at SP in Nobember 2006. The thermal properties were determined on water-saturated specimens. Testing was performed during January 2007.

The controlling documents for the activity are listed in Table 1-1. Activity Plan and Method Descriptions are SKB's (Swedish Nuclear Fuel and Waste Management Company) internal controlling documents. Also SP's (SP Technical Research Institute of Sweden) Quality Plan (SP-QD 13.1) served as controlling document.

Table 1-1. Controlling documents for performance of the activity.

Activity Plan	Number	Version
Selektiv termisk laborationsprovning, Laxemar	AP PS 400-06-141	1.0
Method Description	**Number**	**Version**
Determining thermal conductivity and thermal capacity by the TPS method	SKB MD 191.001	2.0
Metodbeskrivning för bergartsanalyser	SKB MD 160.001	1.0
Quality Plan		
SP-QD 13.1		

2 Objective

The purpose of this activity is to determine the thermal properties of rock specimens. The obtained thermal properties will be used as input data for mechanical and thermal analysis in a site descriptive model that will be established for the candidate area selected for site investigation at Oskarshamn.

3 Equipment

3.1 Transient Plane Source

Technical devices for determination of the thermal properties in question were:

- Kapton sensor 5501, with a radius of 6.403 mm, and a power output of 0.7 W. The sensor 5501 fulfils the recommended relation between sensor radius and sample geometry of the samples in /5/.
- 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.

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

The experimental set-up is shown in Figure 3-2.

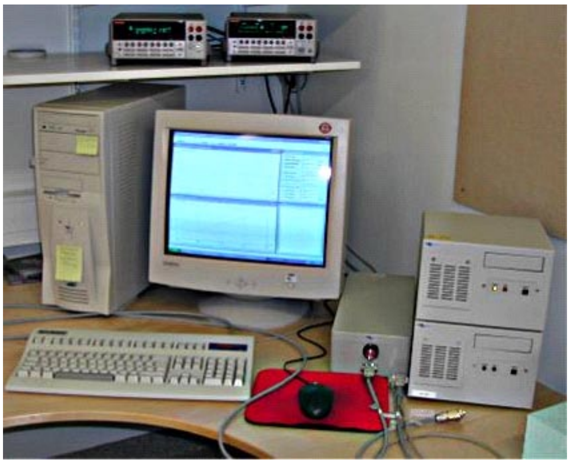

Figure 3-1. *TPS-apparatus with source meter, multi-meter, bridge, and computer.*

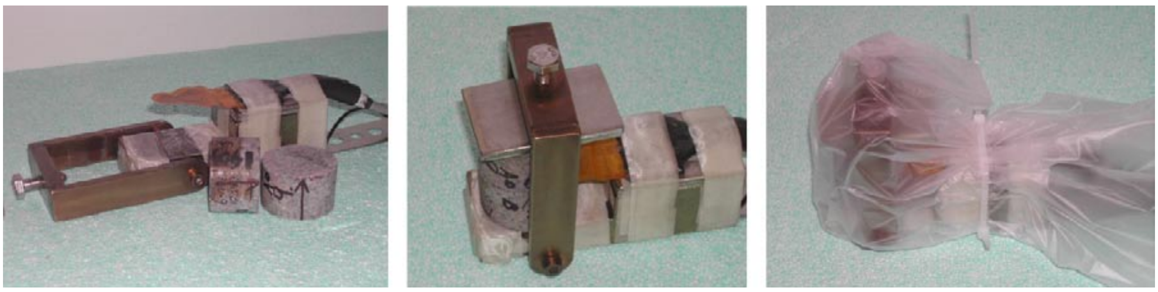

Figure 3-2. *Specimens prior to mounting (left), mounted in stainless sample holder (middle), and sample holder with mounted specimens wrapped in plastic (right).*

3.2 Calorimetric method

The measurement equipment used for the calorimetric determination of the specific heat capacity is partly shown in Figure 3-3 and consisted of:

- Calorimeter, made of Macrolon with low heat capacity and very low heat conductivity.
- Magnetic stirrer, IKA type BigSquid.
- Temperature logger, Keithley 2000 multimeter with scanner Keithley 7700 (temperature resolution 0.01 mK, accuracy 5 mK).
- Temperature controlled bath, Heto Thermostat 13 DT-1 (resolution 0.1°C).
- Three temperature sensors, Pt-100 Pentronic (2 for calorimeter, 1 for temperature controlled bath).
- Thermometer for Air, Pentronic CRL 206, s/n 270210 (resolution 0.01°C).
- Balance Mettler PM 2000 (resolution 0.01 g, accuracy 0.02 g).
- Air conditioning equipment, µAC Carel, Essén Company.
- Laptop computer Toshiba programmed on Visual Basic 6 for the temperature monitoring of three channels per three seconds.
- Pure and de-aerated water, crushed ice for fast preparation of a "steady state" condition.
- Various accessories (stand, holder, clamps, hoses, dewar, syringe, timer, etc).

All measurement instruments are traceable via in-house calibration to national and international standards. The three temperature sensors connected to respective logger channel were calibrated immediately before the measurements. The balance was several times checked using relevant weight pieces.

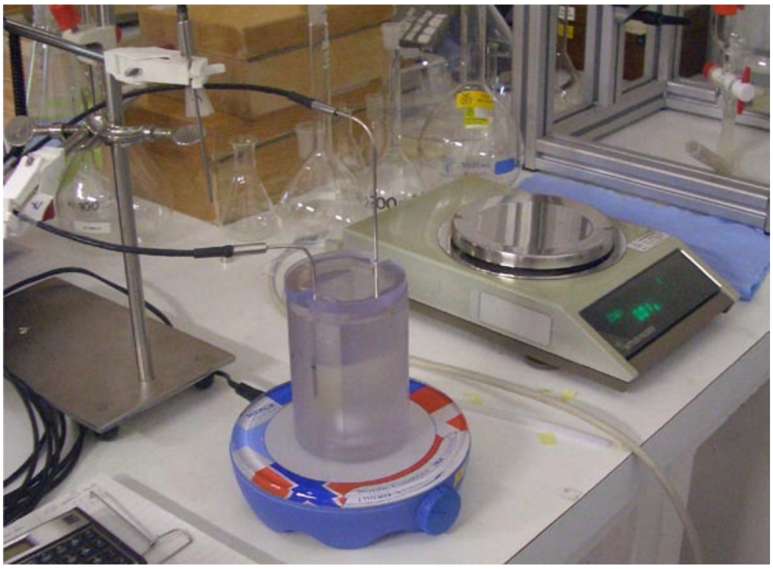

Figure 3-3. *Calorimeter with two temperature sensors on magnetic stirrer.*

4 Execution

Specific heat capacity was determined according to SP-Method 4221 /4/ at SP Measurement Technology.

Determination of thermal properties conductivity and diffusivity was made in compliance with SKB's method description SKB MD 191.001 (SKB internal controlling document) and Hot Disc Instruction Manual /5/ at SP Fire Technology.

The density determinations, which were performed in a parallel activity at SP /3/, were carried out in accordance with SKB MD 160.002 (SKB internal controlling document) and ISRM /6/ at SP Building Technology and Mechanics.

Peter Lau at SP Measurement Technology conducted the specific heat capacity measurements, Bengt Bogren and Ingrid Wetterlund at SP Fire Technology conducted the thermal property measurements and preparation of the report.

4.1 Description of the samples

Thirty-three pairs of cores (designated A and B) and two single specimens were sampled from boreholes KLX03, KLX05, KLX07, KLX10 and KLX11A, Oskarshamn, Sweden. Selective rock samples were taken from earlier investigations in the mentioned boreholes. The samples were taken from the rock types Ävrö granite (501044), Quartz monzodiorite (501036), Diorite/gabbro (501033) and Fine-grained diorite/gabbro (505102). The sixty-six specimens with a thickness of 25 mm each (see Figure 3-2) and the additional two specimens were cut from the rock samples at SP. The diameter of all the specimens was about 50 mm. The identification marks, borehole numbers, rock type, and sampling levels of the specimens are presented in Table 4-1. Detailed geological description of the entire core of the boreholes is given in SKB's database SICADA (Boremap data).

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

Identification	Rock type/ occurence	Sampling level (m borehole length) (Sec low)
KLX03ST-90V-1	(501044)	289.09
KLX03ST-90V-2	(501044)	480.67
KLX03ST-90V-3	(501044)	525.96
KLX07ST-90V-4	(501044)	422.02
KLX07ST-90V-5	(501044)	441.35
KLX07ST-90V-6	(501044)	558.17
KLX07ST-90V-7	(501044)	561.35
KLX07ST-90V-8	(501044)	552.05
KLX10ST-90V-9	(501044)	452.79
KLX10ST-90V-10	(501044)	457.65
KLX10ST-90V-11	(501044)	449.03
KLX10ST-90V-12	(501044)	703.85
KLX10ST-90V-13	(501044)	705.61
KLX10ST-90V-14	(501044)	723.87
KLX05ST-90V-15*	(501033)	371.05
KLX05ST-90V-16*	(501033)	360.67
KLX05ST-90V-17	(501036)	501.61
KLX05ST-90V-18	(501036)	610.82
KLX10ST-90V-19 (KLX10ST-90V-5)**	(501044)	501.84
KLX10ST-90V-20 (KLX10ST-90V-6)**	(501044)	571.51
KLX10ST-90V-21 (KLX10ST-90V-7)**	(501044)	604.70
KLX11ST-90V-22	(501036)	430.30
KLX11ST-90V-23	(501036)	442.75
KLX11ST-90V-24	(501036)	446.12
KLX11ST-90V-25	(501036)	447.79
KLX11ST-90V-26	(501036)	449.47
KLX11ST-90V-27	(501036)	450.44
KLX11ST-90V-28	(501036)	450.82
KLX11ST-90V-29	(501036)	451.51
KLX11ST-90V-30	(501036)	452.85
KLX11ST-90V-31	(501036)	463.30
KLX11ST-90V-32	(501036)	486.43
KLX11ST-90V-33	(501036)	490.32
KLX11ST-90V-34	(505102)	527.22
KLX11ST-90V-35	(505102)	525.06

* Single specimens
** Earlier specimens and identification

4.2 Test procedure

The present activity was performed parallel to other activities, conducted by SP Building Technology and Mechanics, by which the wet and dry density as well as the porosity of the specimens were determined /3/ and by SP Measurement Technology, by which specific heat capacity was determined /4/.

The following logistic sequence was applied for the activities:

1. Specimens were cut and polished by SP Building Technology and Mechanics.
2. Specimens were photographed by SP Building Technology and Mechanics.
3. Specimens were water saturated and wet density was determined by SP Building Technology and Mechanics /3/.
4. Specimens were sent from SP Building Technology and Mechanics to SP Measurement Technology.
5. Specific heat was determined by SP Measurement Technology /4/.
6. Specimens were sent from SP Measurement Technology to SP Fire Technology.
7. Thermal properties were determined by SP Fire Technology.
8. Specimens were sent from SP Fire Technology to SP Building Technology and Mechanics.
9. Dry density of the specimens was determined at SP Building Technology and Mechanics.

The rock samples were water saturated and stored under 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.

Determinations of the thermal properties as well as density and porosity measurements were performed during January–February 2007.

The dry weight was measured after the specimens had been dried to constant mass according to ISMR /6/ at 105°C. The drying procedure took seven days.

4.2.1 Principle of the calorimetric method

The calorimetric technique involves heating the samples after mass determination to a well defined temperature (30°C). The samples are placed in a temperature controlled water bath long enough time to stabilize.

The calorimeter is filled with prepared water (pure and de-aerated of 18°C) to a predefined level and stirred to produce nearly steady state conditions. Thereafter it is placed on the balance and excessive water is extracted with a syringe to reach a nominal mass, chosen with respect to the sample volume.

The so prepared calorimeter is stirred and the temperature logging program is started. After 90 to 150 seconds the sample is quickly moved (3 to 5 seconds) from the bath into the calorimeter. The temperature rise of water can be followed graphically during the equalization process, which typically takes 150 seconds and the experiment is terminated after another 300 to 600 seconds.

The calorimeter, water and sample are weighed again to determine the amount of water that unavoidably did follow with the sample into the calorimeter. This amount is typically 0.28 to 0.36% of the water contained in the calorimeter. If accidentally a water splash happens during the sample insertion, those droplets are absorbed with a small piece of prepared tissue that is weighed dry and wet. The corresponding mass is subtracted from the initial water mass. In extreme cases it has amounted to 0.03% of the total water mass.

All mass values for the determination of the specific heat were manually documented in a prepared form that was a printout of the corresponding Excel calculation sheet.

With the termination of the logging program each experiment was saved as raw data in an Excel file on the SP network. The main information was the bath temperature and two calorimeter temperatures as function of time. Finally, the specific heat capacity can be calculated by using the measured parameters.

Each sample value means two separate measurements one for sample A and one for sample B and the reported result represents the average of both.

4.2.2 Principle of Transient Plane Source

The principle of the TPS-method is to install a sensor consisting of a thin metal double spiral, embedded in an insulation material, between two rock samples. 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 thermal conductivity and diffusivity of a material.

The thermal properties of the water-saturated specimens were measured in ambient air (20°C). In order to remain water saturation and obtain desired temperature, the specimens and the sensor were kept in a plastic bag during the measurements, see Figure 3-2.

Each pair of specimens (A and B) 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.

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

4.3 Nonconformities

Specimen KLX13 cracked after measuring thermal properties. The crack did probably exist during measurement of thermal properties. A crack in a specimen can influence the measured results.

5 Results

The results of activity are stored in SKB´s database SICADA, where they are traceable by the Activity Plan number.

Mean values of measured thermal properties by TPS, five repeated measurements, are reported in 5.1 and in 5.2. Values of each separate measurement as described in Section 5.1 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.

The specific heat capacity and the calculated volumetric heat capacity for each separate sample are reported in 5.1 and in 5.2.

The results from the modal analysis are reported in Appendix D.

5.1 Test results of individual specimens

Specimens KLX03ST-90V-1A and B

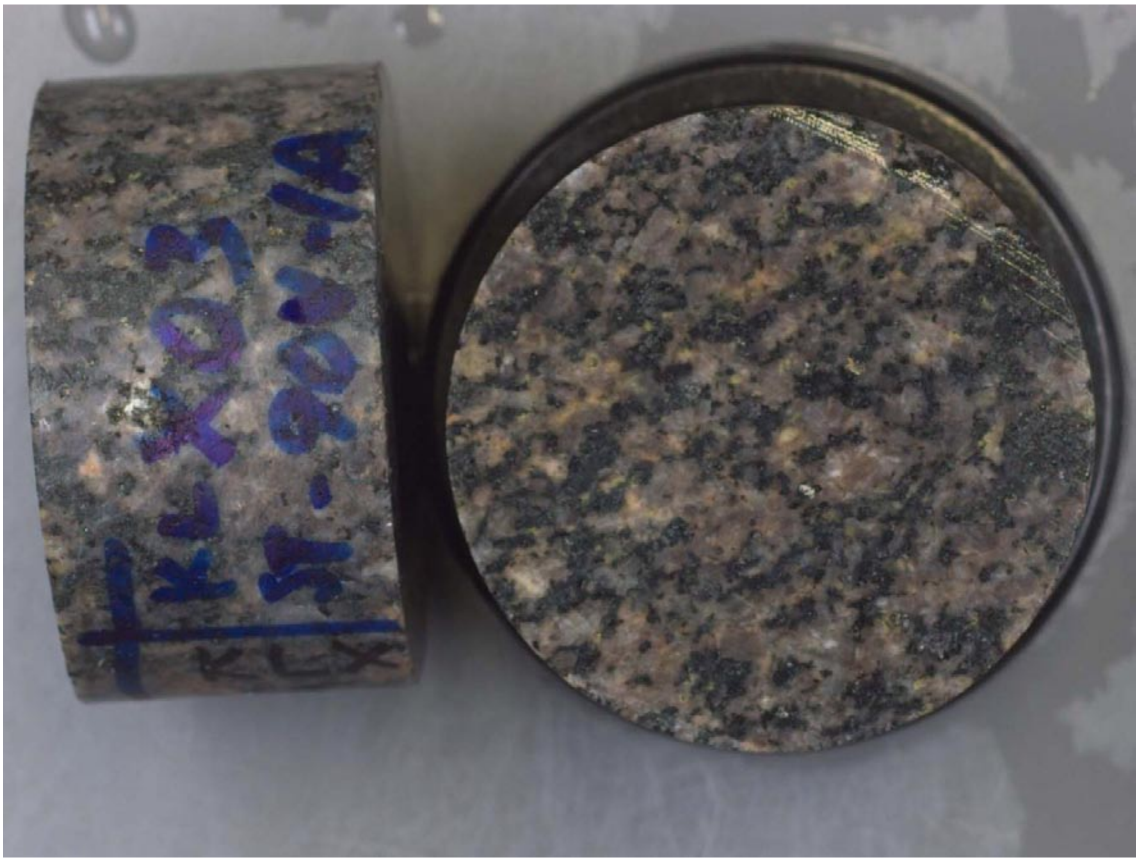

Figure 5-1. *Specimens KLX03ST-90V-1A and B.*

Table 5-1. Porosity, wet and dry density of specimens KLX03ST-90V-1A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX03ST-90V-1 Sec low: 289.09	2,790	2,790	0.3

Table 5-2. Thermal properties of specimens KLX03ST-90V-1A and B at ambient temperature, average values.

Sample KLX03ST-90V-1 Sec low: 289.09	TPS method Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]	Calorimeter Calculated heat capacity [MJ/(m³, K)]	Heat capacity [J/(g, K)]
Mean value	2.24	0.97	2.31	2.17	0.777
Standard deviation	0.012	0.024	0.050	–	–

Specimens KLX03ST-90V-2A and B

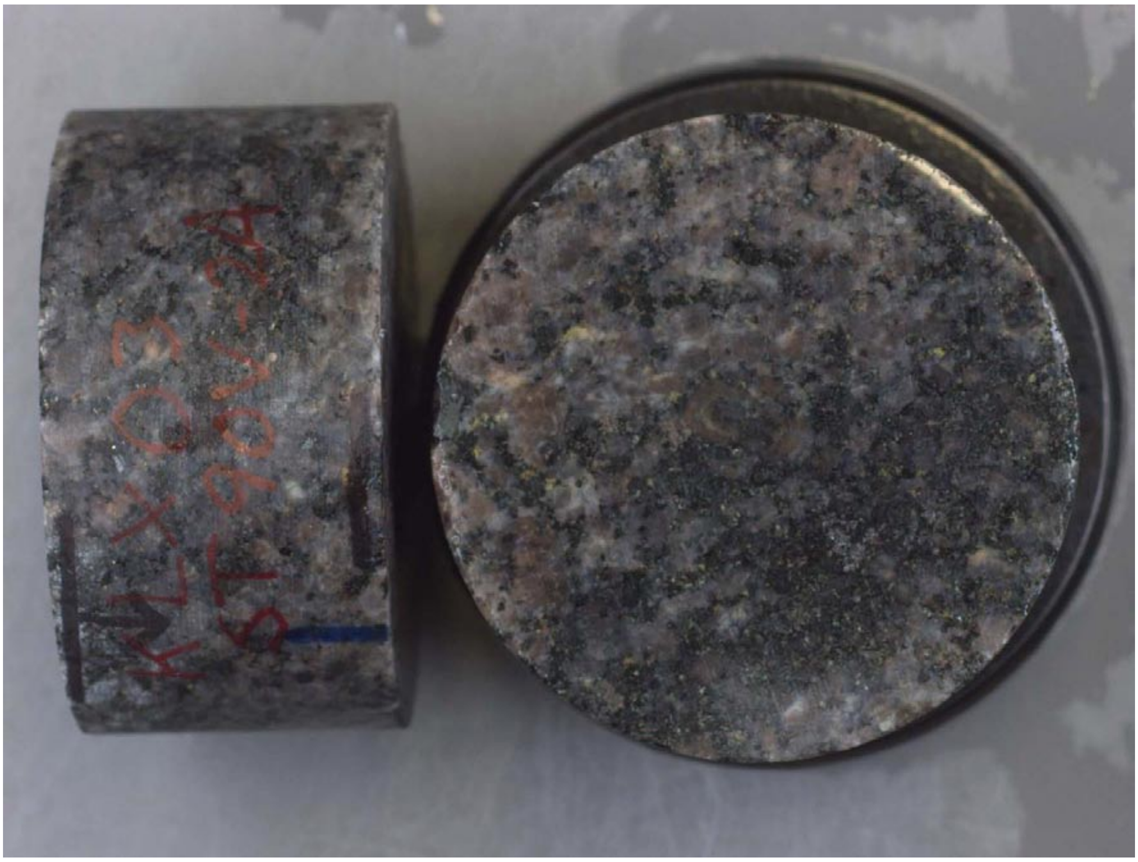

Figure 5-2. *Specimens KLX03ST-90V-2A and B.*

Table 5-3. Porosity, wet and dry density of specimens KLX03ST-90V-2A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX03ST-90V-2 Sec low: 480.67	2,760	2,750	0.5

Table 5-4. Thermal properties of specimens KLX03ST-90V-2A and B at ambient temperature, average values.

Sample KLX03ST-90V-2 Sec low: 480.67	TPS method Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]	Calorimeter Calculated heat capacity [MJ/(m³, K)]	Heat capacity [J/(g, K)]
Mean value	2.56	1.16	2.20	2.10	0.762
Standard deviation	0.005	0.010	0.021	–	–

Specimens KLX03ST-90V-3A and B

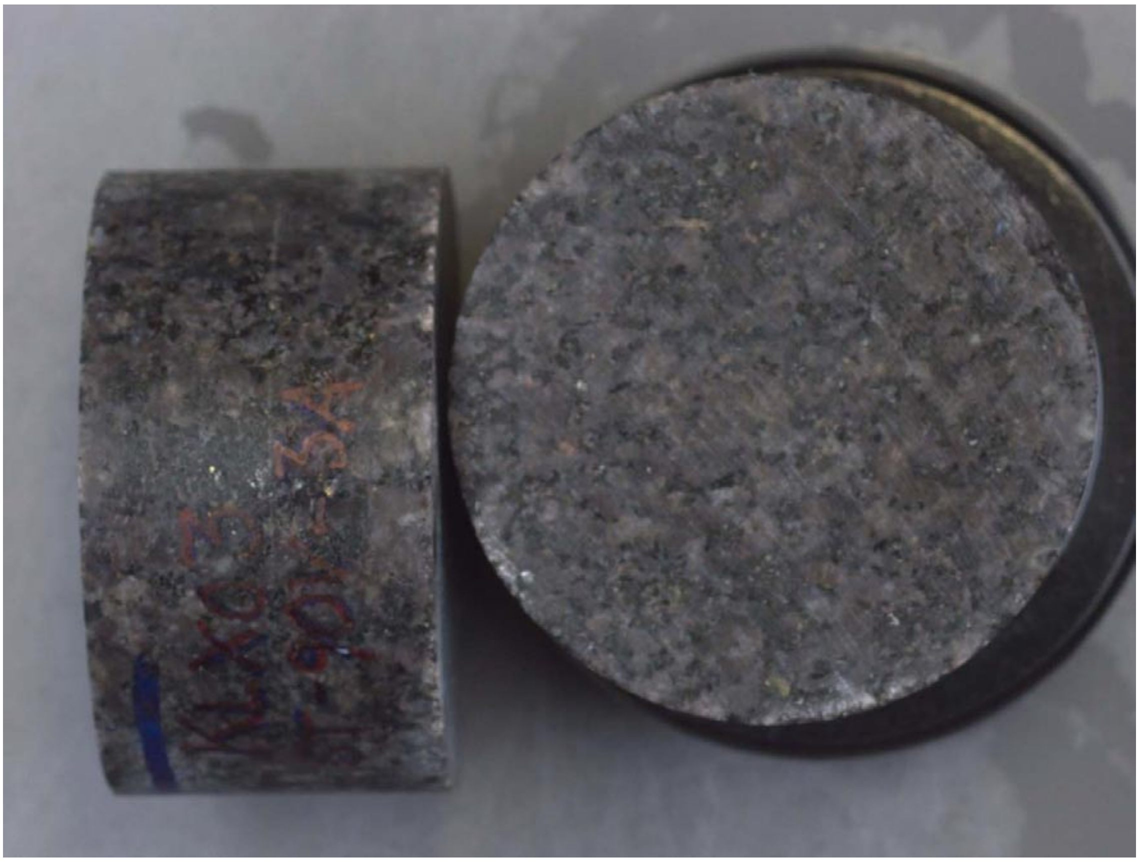

Figure 5-3. *Specimens KLX03ST-90V-3A and B.*

Table 5-5. Porosity, wet and dry density of specimens KLX03ST-90V-3A and B, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
KLX03ST-90V-3 Sec low: 525.96	2,780	2,780	0.5

Table 5-6. Thermal properties of specimens KLX03ST-90V-3A and B at ambient temperature, average values, TPS-method.

KLX03ST-90V-3 Sec low: 525.96	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]
Mean value	2.22	0.97	2.30
Standard deviation	0.004	0.010	0.023

Specimens KLX07ST-90V-4A and B.

Figure 5-4. *Specimens KLX07ST-90V-4A and B.*

Table 5-7. Porosity, wet and dry density of specimens KLX07ST-90V-4A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX07ST-90V-4 Sec low: 422.02	2,690	2,680	0.6

Table 5-8. Thermal properties of specimens KLX07ST-90V-4A and B at ambient temperature, average values, TPS-method.

KLX07ST-90V-4 Sec low: 422.02	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	3.17	1.52	2.09
Standard deviation	0.006	0.016	0.025

Specimens KLX07ST-90V-5A and B

Figure 5-5. *Specimens KLX07ST-90V-5A and B.*

Table 5-9. Porosity, wet and dry density of specimens KLX07ST-90V-5A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX07ST-90V-5 Sec low: 441.35	2,690	2,680	0.5

Table 5-10. Thermal properties of specimens KLX07ST-90V-5A and B at ambient temperature, average values.

Sample KLX07ST-90V-5 Sec low: 441.35	TPS method Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]	Calorimeter Calculated heat capacity [MJ/(m³, K)]	Heat capacity [J/(g, K)]
Mean value	3.10	1.64	1.89	2.10	0.780
Standard deviation	0.028	0.065	0.059	–	–

Specimens KLX07ST-90V-6A and B

Figure 5-6. *Specimens KLX07ST-90V-6A and B.*

Table 5-11. Porosity, wet and dry density of specimens KLX07ST-90V-6A and B, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
KLX07ST-90V-6 Sec low: 558.17	2,670	2,660	0.9

Table 5-12. Thermal properties of specimens KLX07ST-90V-6A and B at ambient temperature, average values, TPS-method.

KLX07ST-90V-6 Sec low: 558.17	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]
Mean value	3.48	1.48	2.35
Standard deviation	0.006	0.007	0.015

Specimens KLX07ST-90V-7A and B

Figure 5-7. *Specimens KLX07ST-90V-7A and B.*

Table 5-13. Porosity, wet and dry density of specimens KLX07ST-90V-7A and B, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
KLX07ST-90V-7 Sec low: 561.35	2,690	2,690	0.4

Table 5-14. Thermal properties of specimens KLX07ST-90V-7A and B at ambient temperature, average values, TPS-method.

KLX07ST-90V-7 Sec low: 561.35	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]
Mean value	3.26	1.52	2.14
Standard deviation	0.018	0.051	0.080

Specimens KLX07ST-90V-8A and B

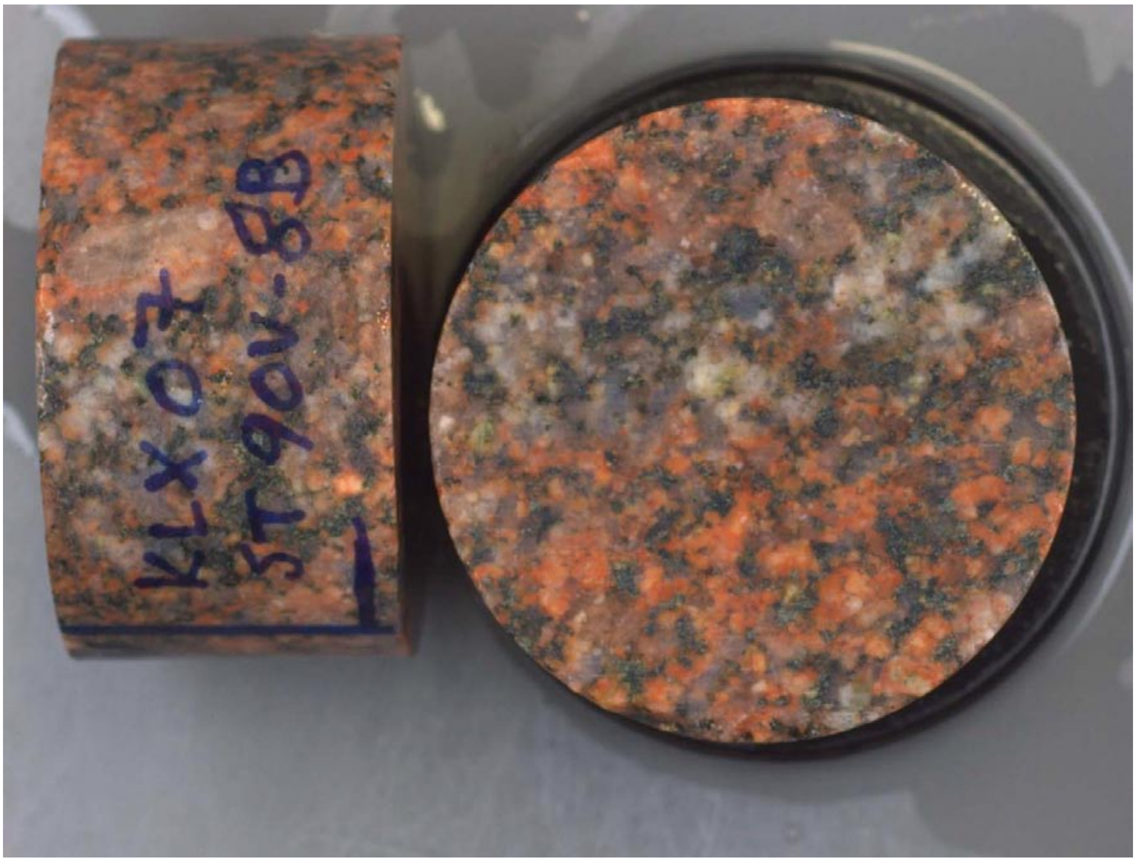

Figure 5-8. *Specimens KLX07ST-90V-8A and B.*

Table 5-15. Porosity, wet and dry density of specimens KLX07ST-90V-8A and B, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
KLX07ST-90V-8 Sec low: 552.05	2,690	2,680	0.4

Table 5-16. Thermal properties of specimens KLX07ST-90V-8A and B at ambient temperature, average values, TPS-method.

KLX07ST-90V-8 Sec low: 552.05	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]
Mean value	3.05	1.49	2.04
Standard deviation	0.007	0.010	0.018

Specimens KLX10ST-90V-9A and B

Figure 5-9. *Specimens KLX10ST-90V-9A and B.*

Table 5-17. Porosity, wet and dry density of specimens KLX10ST-90V-9A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX10ST-90V-9 Sec low: 452.79	2,670	2,660	0.7

Table 5-18. Thermal properties of specimens KLX10ST-90V-9A and B at ambient temperature, average values.

Sample KLX10ST-90V-9 Sec low: 452.79	TPS method Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]	Calorimeter Calculated heat capacity [MJ/(m³, K)]	Heat capacity [J/(g, K)]
Mean value	3.28	1.55	2.12	2.13	0.800
Standard deviation	0.004	0.009	0.014	–	–

Specimens KLX10ST-90V-10A and B

Figure 5-10. *Specimens KLX10ST-90V-10A and B.*

Table 5-19. Porosity, wet and dry density of specimens KLX10ST-90V-10A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX10ST-90V-10 Sec low: 457.65	2,670	2,670	0.7

Table 5-20. Thermal properties of specimens KLX10ST-90V-10A and B at ambient temperature, average values, TPS-method.

KLX10ST-90V-10 Sec low: 457.65	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	3.39	1.53	2.21
Standard deviation	0.003	0.003	0.007

Specimens KLX10ST-90V-11A and B

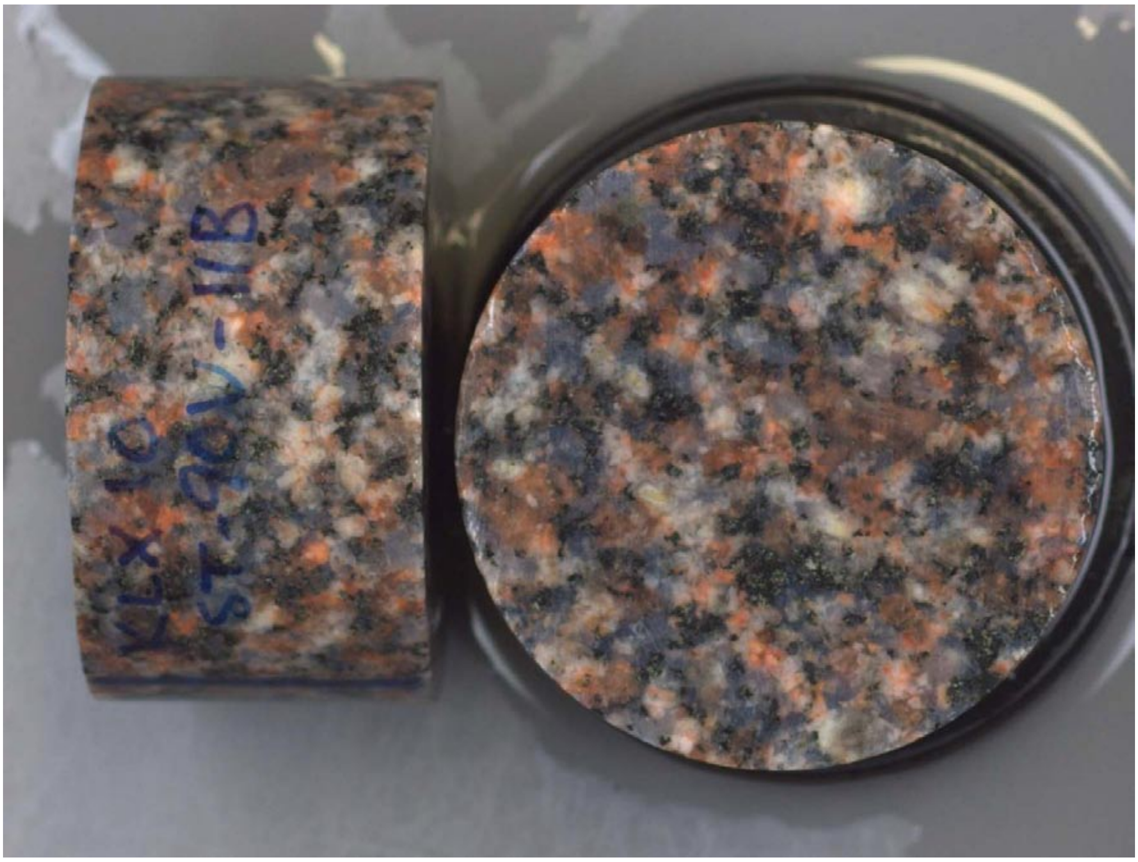

Figure 5-11. *Specimens KLX10ST-90V-11A and B.*

Table 5-21. Porosity, wet and dry density of specimens KLX10ST-90V-11A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX10ST-90V-11 Sec low: 449.03	2,690	2,680	0.5

Table 5-22. Thermal properties of specimens KLX10ST-90V-11A and B at ambient temperature, average values, TPS-method.

KLX10ST-90V-11 Sec low: 449.03	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	3.02	1.53	1.98
Standard deviation	0.013	0.037	0.054

Specimens KLX10ST-90V-12A and B

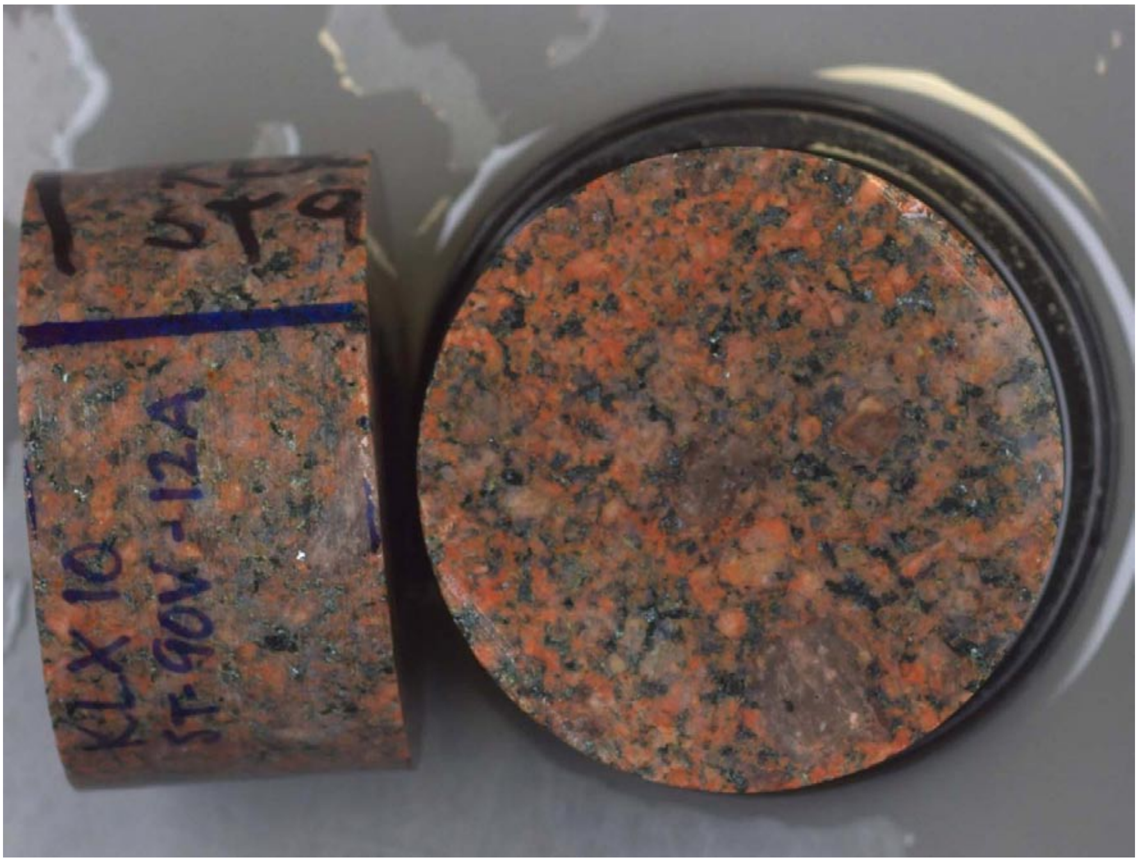

Figure 5-12. *Specimens KLX10ST-90V-12A and B.*

Table 5-23. Porosity, wet and dry density of specimens KLX10ST-90V-12A and B, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
KLX10ST-90V-12 Sec low: 703.85	2,720	2,710	0.6

Table 5-24. Thermal properties of specimens KLX10ST-90V-12A and B at ambient temperature, average values.

Sample KLX10ST-90V-12 Sec low: 703.85	TPS method Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]	Calorimeter Calculated heat capacity [MJ/(m^3, K)]	Heat capacity [J/(g, K)]
Mean value	2.52	1.18	2.14	2.12	0.780
Standard deviation	0.005	0.007	0.014	–	–

Specimens KLX10ST-90V-13A and B

Figure 5-13. *Specimens KLX10ST-90V-13A and B.*

Table 5-25. Porosity, wet and dry density of specimens KLX10ST-90V-13A and B, average values.

Sample	Density, wet [kg/m^3]	Density, dry [kg/m^3]	Porosity [%]
KLX10ST-90V-13 Sec low: 705.61	2,730	2,720	1.1

Table 5-26. Thermal properties of specimens KLX10ST-90V-13A and B at ambient temperature, average values, TPS-method.

KLX10ST-90V-13 Sec low: 705.61	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [MJ/(m^3, K)]
Mean value	2.59	1.38	1.87
Standard deviation	0.013	0.033	0.050

Specimens KLX10ST-90V-14A and B.

Figure 5-14. *Specimens KLX10ST-90V-14A and B.*

Table 5-27. Porosity, wet and dry density of specimens KLX10ST-90V-14A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX10ST-90V-14 Sec low: 723.87	2,730	2,720	0.5

Table 5-28. Thermal properties of specimens KLX10ST-90V-14A and B at ambient temperature, average values.

Sample KLX10ST-90V-14 Sec low: 723.87	TPS method Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]	Calorimeter Calculated heat capacity [MJ/(m³, K)]	Heat capacity [J/(g, K)]
Mean value	2.52	1.26	1.99	2.12	0.777
Standard deviation	0.005	0.006	0.014	–	–

Specimen KLX05ST-90V-15

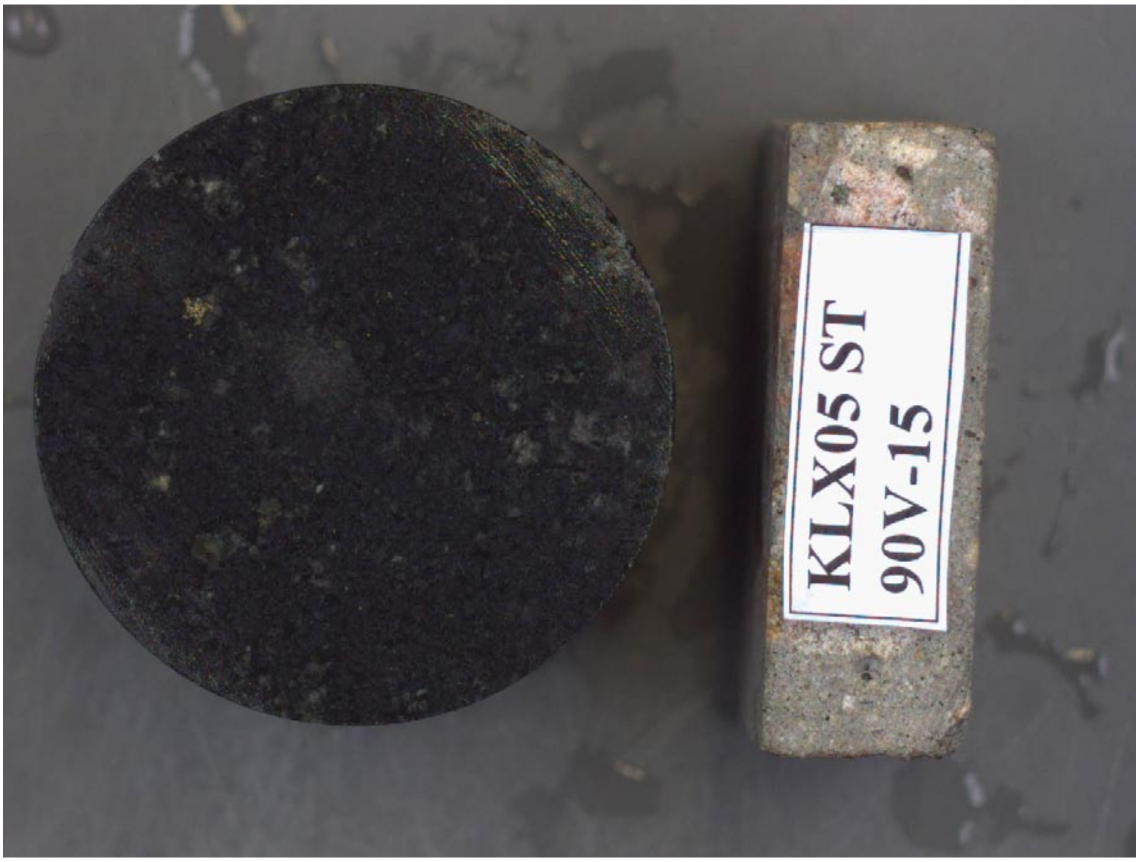

Figure 5-15. *Specimen KLX05ST-90V-15 (left part of picture).*

Table 5-29. Porosity, wet and dry density of specimen KLX05ST-90V-15, values from one single specimen.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX05ST-90V-15 Sec low: 371.05	2,930	2,930	0.1

Table 5-30. Heat capacity of specimen KLX05ST-90V-15, values from one single specimen.

Sample	Specific heat capacity [J/(g, K)]	Calculated volumetric heat capacity [MJ/(m³, K)]
KLX05ST-90V-15 Sec low: 371.05	2.38	0.814

Specimen KLX05ST-90V-16

Figure 5-16. *Specimen KLX05ST-90V-16 (left part of picture).*

Table 5-31. Porosity, wet and dry density of specimen KLX05ST-90V-16, values from one single specimen.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX05ST-90V-16 Sec low: 360.67	3,030	3,020	0.1

Table 5-32. Heat capacity of specimen KLX05ST-90V-16, values from one single specimen.

Sample	Specific heat capacity [J/(g, K)]	Calculated volumetric heat capacity [MJ/(m³, K)]
KLX05ST-90V-16 Sec low: 360.67	2.46	0.814

Specimens KLX05ST-90V-17A and B

Figure 5-17. *Specimens KLX05ST-90V-17A and B.*

Table 5-33. Porosity, wet and dry density of specimens KLX05ST-90V-17A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX05ST-90V-17 Sec low: 501.61	2,900	2,900	0.2

Table 5-34. Thermal properties of specimens KLX05ST-90V-17A and B at ambient temperature, average values.

Sample KLX05ST-90V-17 Sec low: 501.61	TPS method Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]	Calorimeter Calculated heat capacity [MJ/(m³, K)]	Heat capacity [J/(g, K)]
Mean value	3.24	1.26	2.56	2.33	0.804
Standard deviation	0.006	0.003	0.012	–	–

Specimens KLX05ST-90V-18A and B

Figure 5-18. *Specimens KLX05ST-90V-18A and B.*

Table 5-35. Porosity, wet and dry density of specimens KLX05ST-90V-18A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX05ST-90V-18 Sec low: 610.82	2,780	2,780	0.2

Table 5-36. Thermal properties of specimens KLX05ST-90V-18A and B at ambient temperature, average values, TPS-method.

KLX05ST-90V-18 Sec low: 610.82	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	3.30	1.47	2.24
Standard deviation	0.008	0.016	0.029

Specimens KLX10ST-90V-19A and B

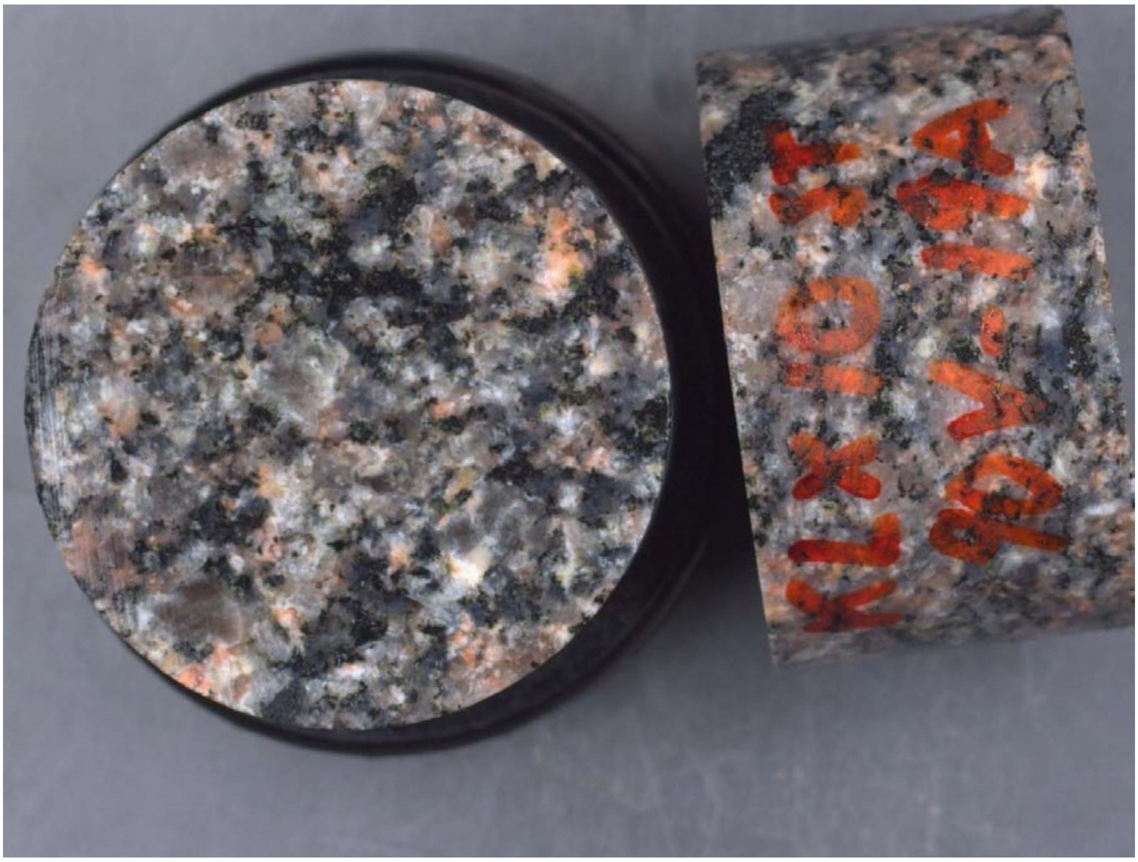

Figure 5-19. *Specimens KLX10ST-90V-19A and B.*

Table 5-37. Porosity, wet and dry density of specimens KLX10ST-90V-19A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX10ST-90V-19 Sec low: 501.84	2,680	2,680	0.4

Table 5-38. Heat capacity of specimens KLX10ST-90V-19A and B, average values.

Sample	Specific heat capacity [J/(g, K)]	Calculated volumetric heat capacity [MJ/(m³, K)]
KLX10ST-90V-19 Sec low: 501.84	2.16	0.805

Specimens KLX10ST-90V-20A and B

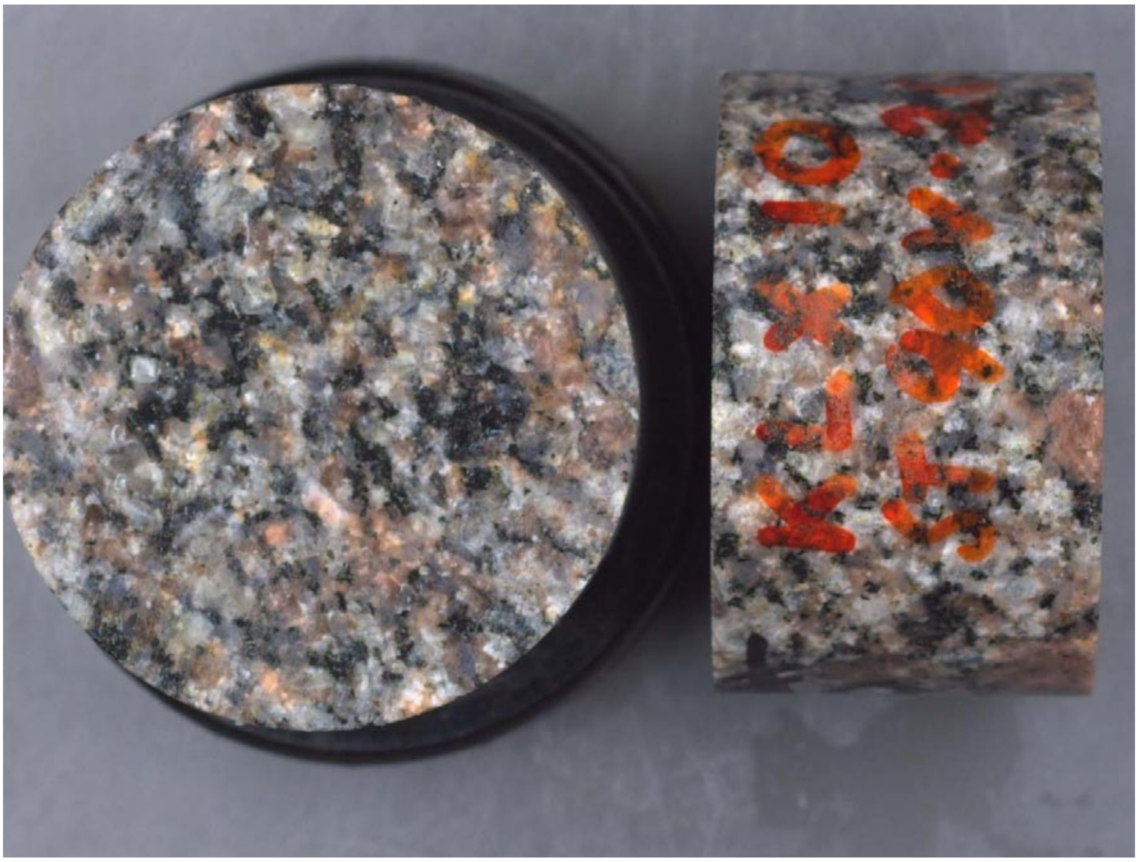

Figure 5-20. *Specimens KLX10ST-90V-20A and B.*

Table 5-39. Porosity, wet and dry density of specimens KLX10ST-90V-20A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX10ST-90V-20 Sec low: 571.51	2,680	2,680	0.4

Table 5-40. Heat capacity of specimens KLX10ST-90V-20A and B, average values.

Sample	Specific heat capacity [J/(g, K)]	Calculated volumetric heat capacity [MJ/(m³, K)]
KLX10ST-90V-20 Sec low: 571.51	2.14	0.797

Specimens KLX10ST-90V-21A and B

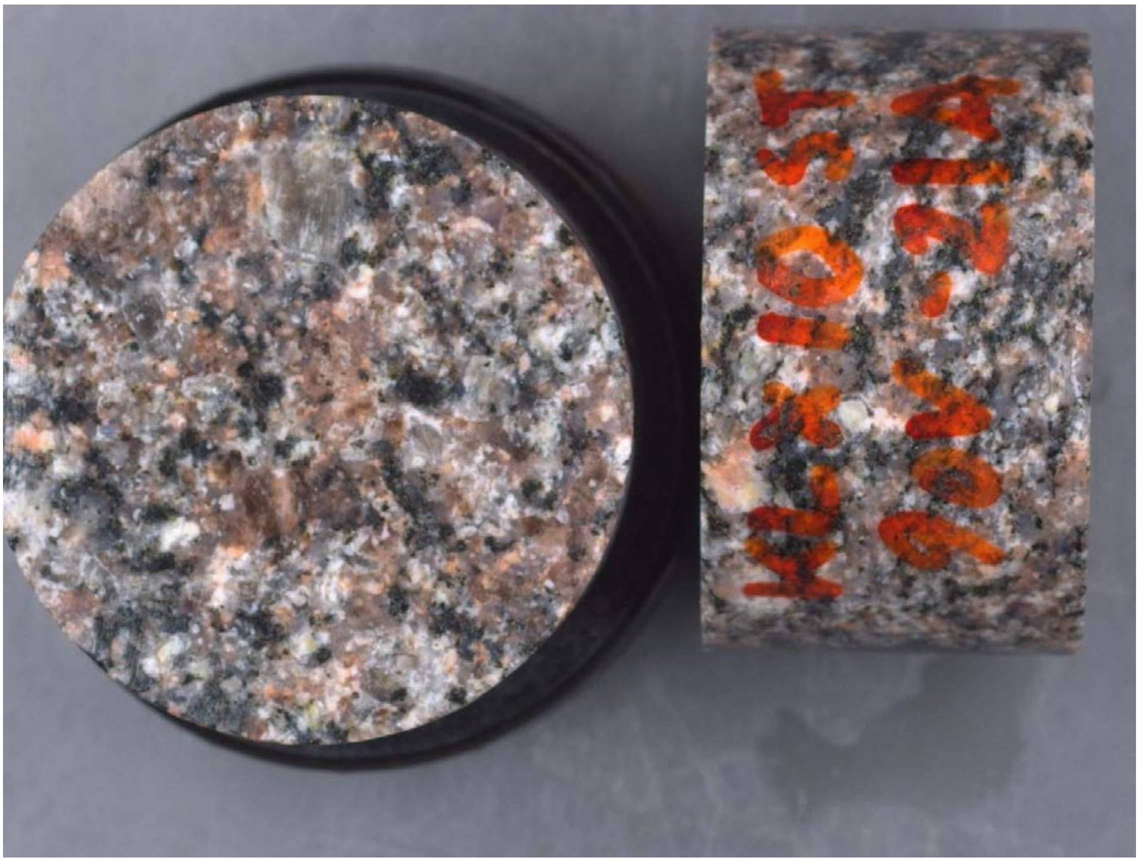

Figure 5-21. *Specimens KLX10ST-90V-21A and B.*

Table 5-41. Porosity, wet and dry density of specimens KLX10ST-90V-21A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX10ST-90V-21 Sec low: 604.70	2,680	2,670	0.4

Table 5-42. Heat capacity of specimens KLX10ST-90V-21A and B, average values.

Sample	Specific heat capacity [J/(g, K)]	Calculated volumetric heat capacity [MJ/(m³, K)]
KLX10ST-90V-21 Sec low: 604.70	2.11	0.790

Specimens KLX11ST-90V-22A and B

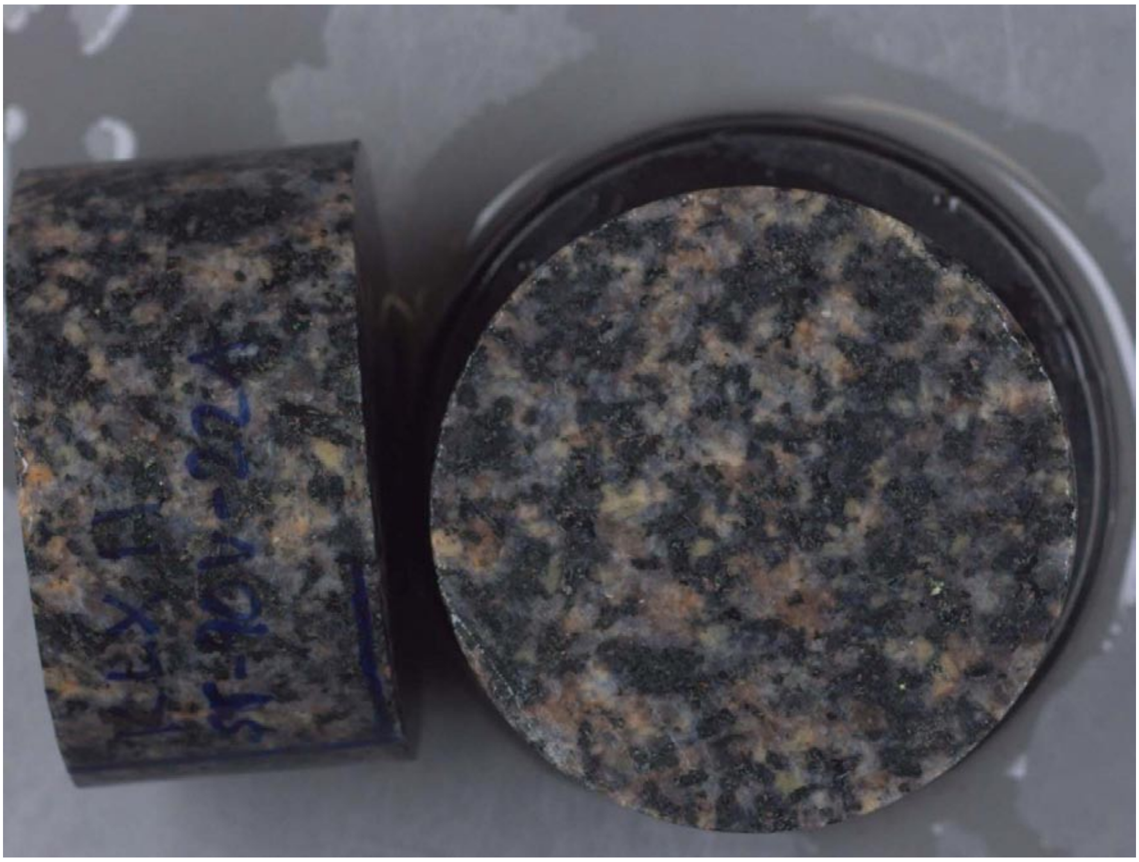

Figure 5-22. *Specimens KLX11ST-90V-22A and B.*

Table 5-43. Porosity, wet and dry density of specimens KLX11ST-90V-22A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-22 Sec low: 430.30	2,780	2,780	0.2

Table 5-44. Thermal properties of specimens KLX11ST-90V-22A and B at ambient temperature, average values, TPS-method.

KLX11ST-90V-22 Sec low: 430.30	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	2.75	1.15	2.39
Standard deviation	0.006	0.004	0.010

Specimens KLX11ST-90V-23A and B

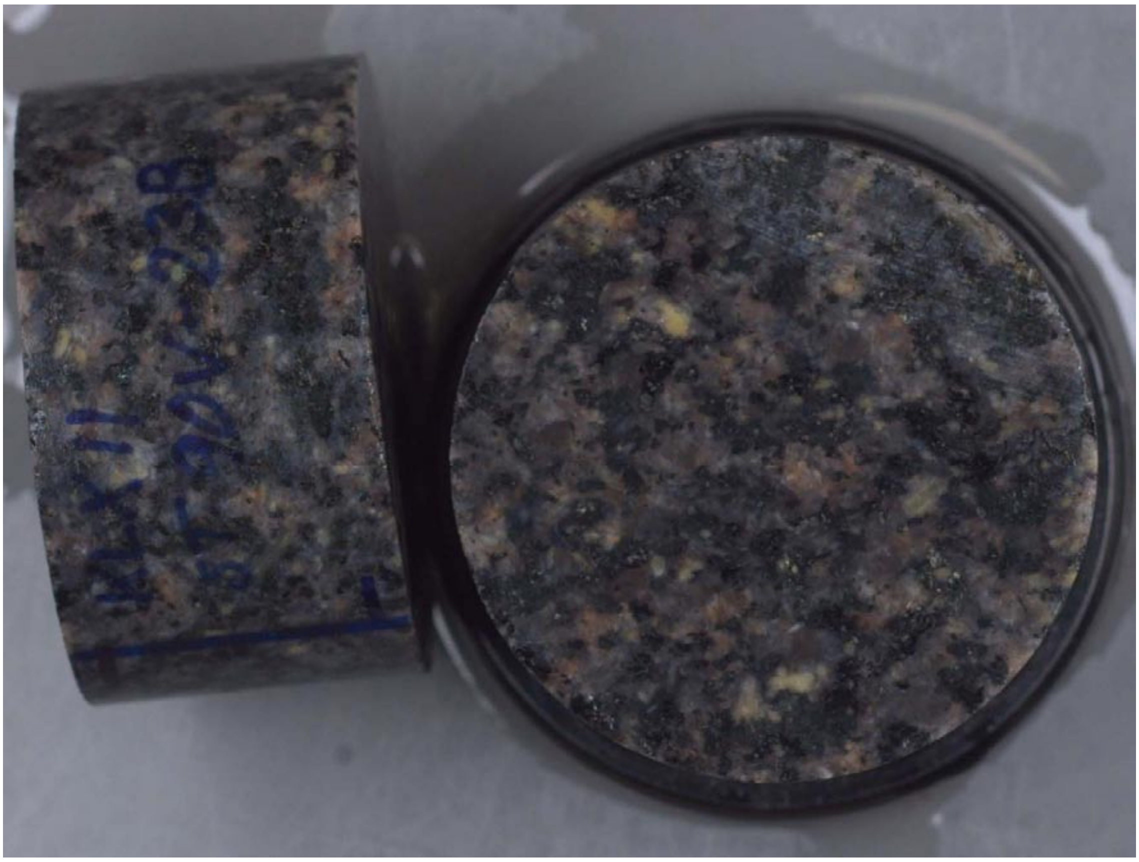

Figure 5-23. *Specimens KLX11ST-90V-23A and B.*

Table 5-45. Porosity, wet and dry density of specimens KLX11ST-90V-23A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-23 Sec low: 442.75	2,780	2,770	0.3

Table 5-46. Thermal properties of specimens KLX11ST-90V-23A and B at ambient temperature, average values, TPS-method.

KLX11ST-90V-23 Sec low: 442.75	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	2.61	1.22	2.14
Standard deviation	0.005	0.006	0.014

Specimens KLX11ST-90V-24A and B

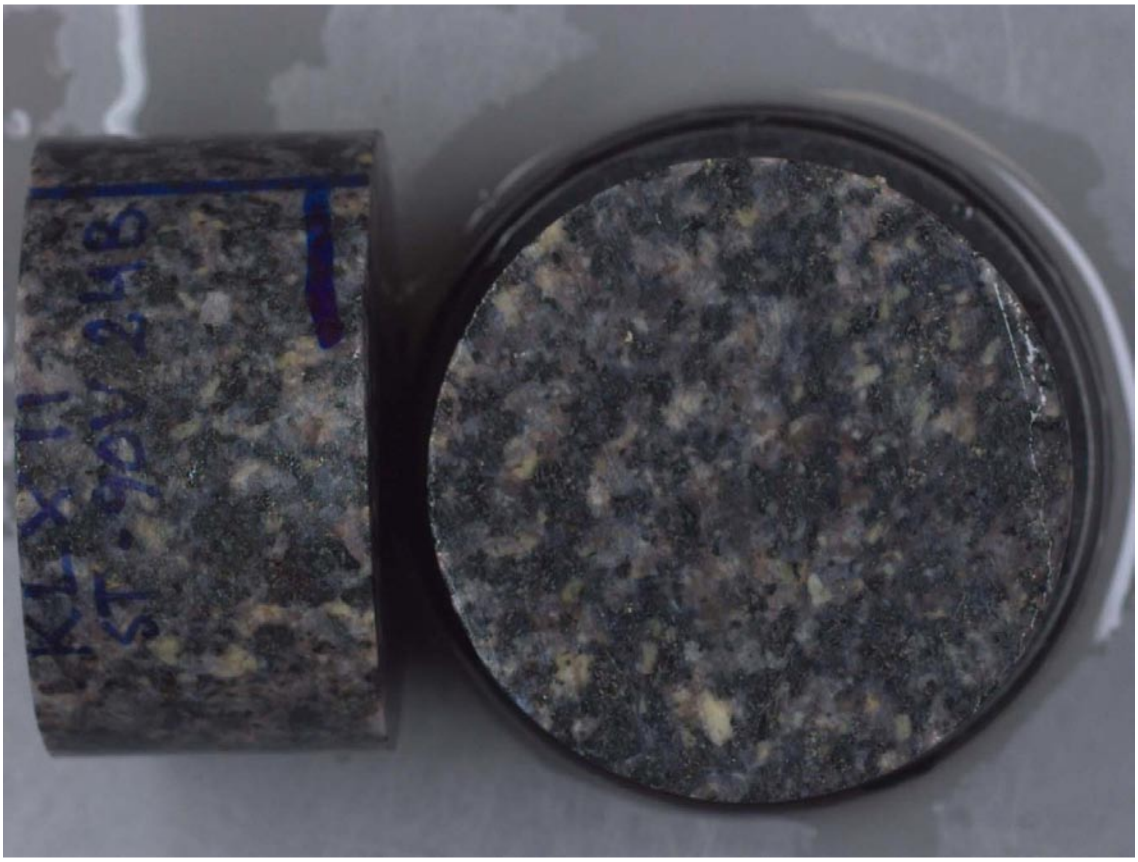

Figure 5-24. *Specimens KLX11ST-90V-24A and B.*

Table 5-47. Porosity, wet and dry density of specimens KLX11ST-90V-24A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-24 Sec low: 446.12	2,790	2,790	0.2

Table 5-48. Thermal properties of specimens KLX11ST-90V-24A and B at ambient temperature, average values, TPS-method.

KLX11ST-90V-24 Sec low: 446.12	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	2.61	1.23	2.12
Standard deviation	0.005	0.008	0.017

Specimens KLX11ST-90V-25A and B

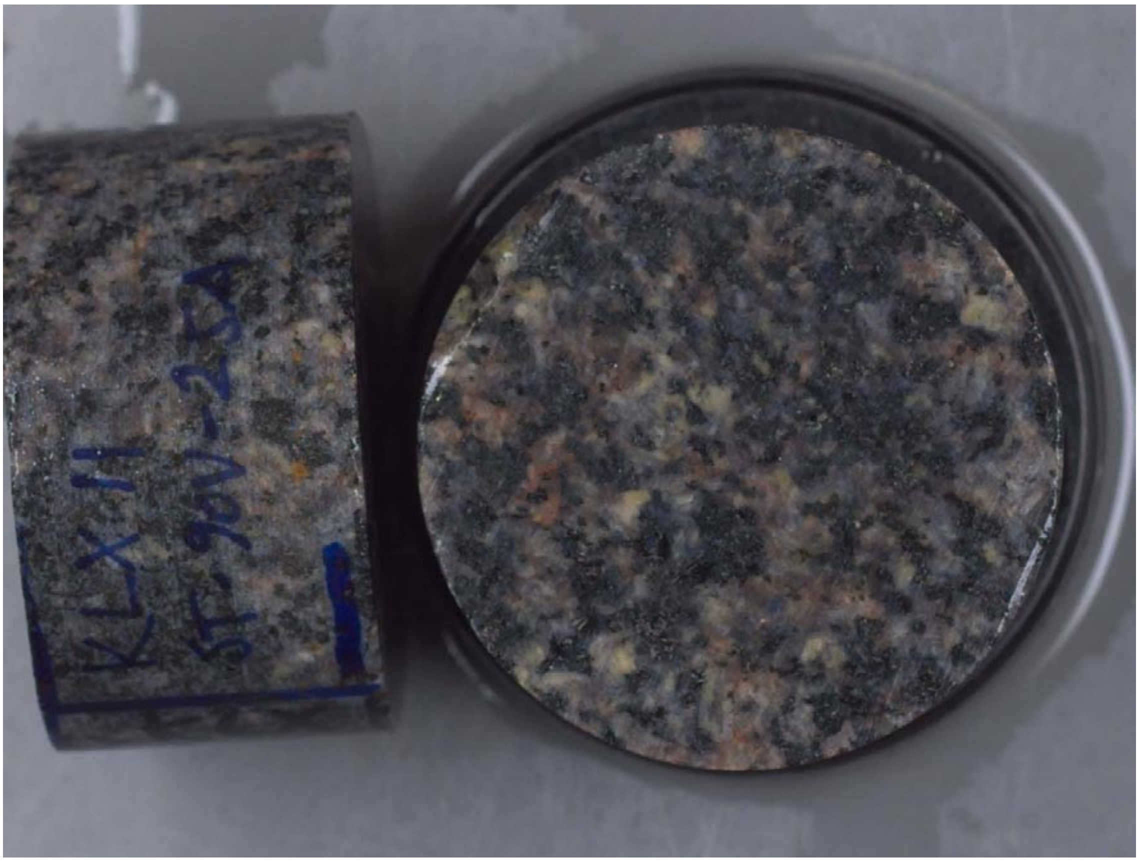

Figure 5-25. *Specimens KLX11ST-90V-25A and B.*

Table 5-49. Porosity, wet and dry density of specimens KLX11ST-90V-25A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-25 Sec low: 447.79	2,780	2,770	0.2

Table 5-50. Thermal properties of specimens KLX11ST-90V-25A and B at ambient temperature, average values, TPS-method.

KLX11ST-90V-25 Sec low: 447.79	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	2.60	1.23	2.12
Standard deviation	0.004	0.004	0.009

Specimens KLX11ST-90V-26A and B

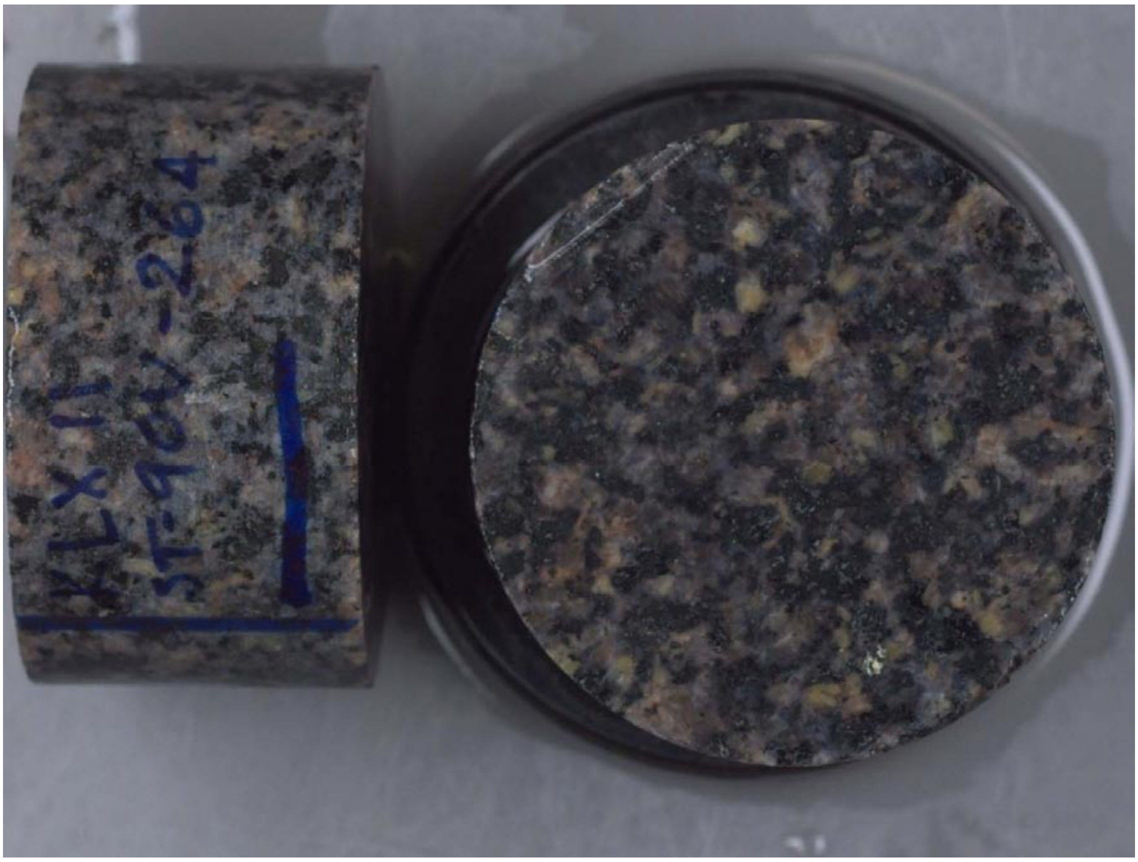

Figure 5-26. *Specimens KLX11ST-90V-26A and B.*

Table 5-51. Porosity, wet and dry density of specimens KLX11ST-90V-26A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-26 Sec low: 449.47	2,780	2,780	0.2

Table 5-52. Thermal properties of specimens KLX11ST-90V-26A and B at ambient temperature, average values, TPS-method.

KLX11ST-90V-26 Sec low: 449.47	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	2.66	1.25	2.13
Standard deviation	0.006	0.007	0.016

Specimens KLX11ST-90V-27A and B

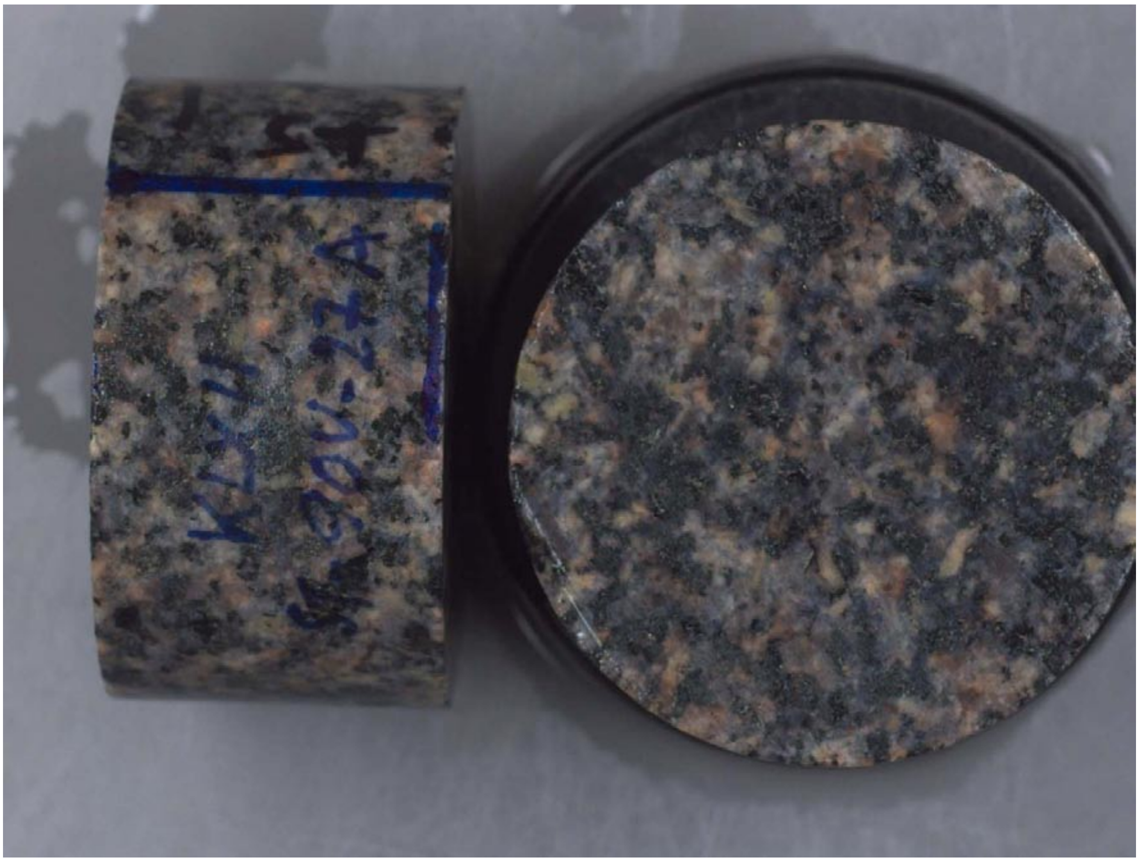

Figure 5-27. *Specimens KLX11ST-90V-27A and B.*

Table 5-53. Porosity, wet and dry density of specimens KLX11ST-90V-27A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-27 Sec low: 450.44	2,780	2,780	0.3

Table 5-54. Thermal properties of specimens KLX11ST-90V-27A and B at ambient temperature, average values, TPS-method.

KLX11ST-90V-27 Sec low: 450.44	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	2.67	1.24	2.16
Standard deviation	0.004	0.022	0.041

Specimens KLX11ST-90V-28A and B

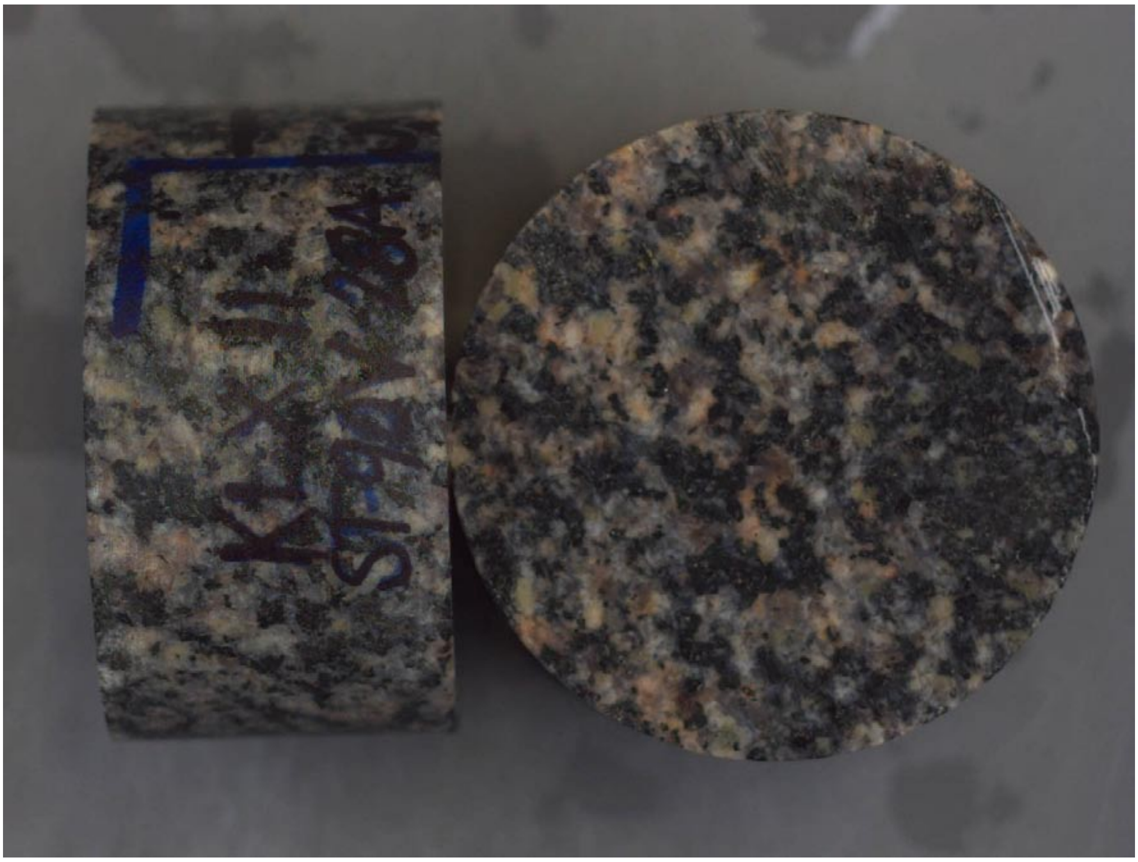

Figure 5-28. *Specimens KLX11ST-90V-28A and B.*

Table 5-55. Porosity, wet and dry density of specimens KLX11ST-90V-28A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-28 Sec low: 450.82	2,780	2,780	0.3

Table 5-56. Thermal properties of specimens KLX11ST-90V-28A and B at ambient temperature, average values, TPS-method.

KLX11ST-90V-28 Sec low: 450.82	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	2.74	1.27	2.15
Standard deviation	0.009	0.010	0.024

Specimens KLX11ST-90V-29A and B

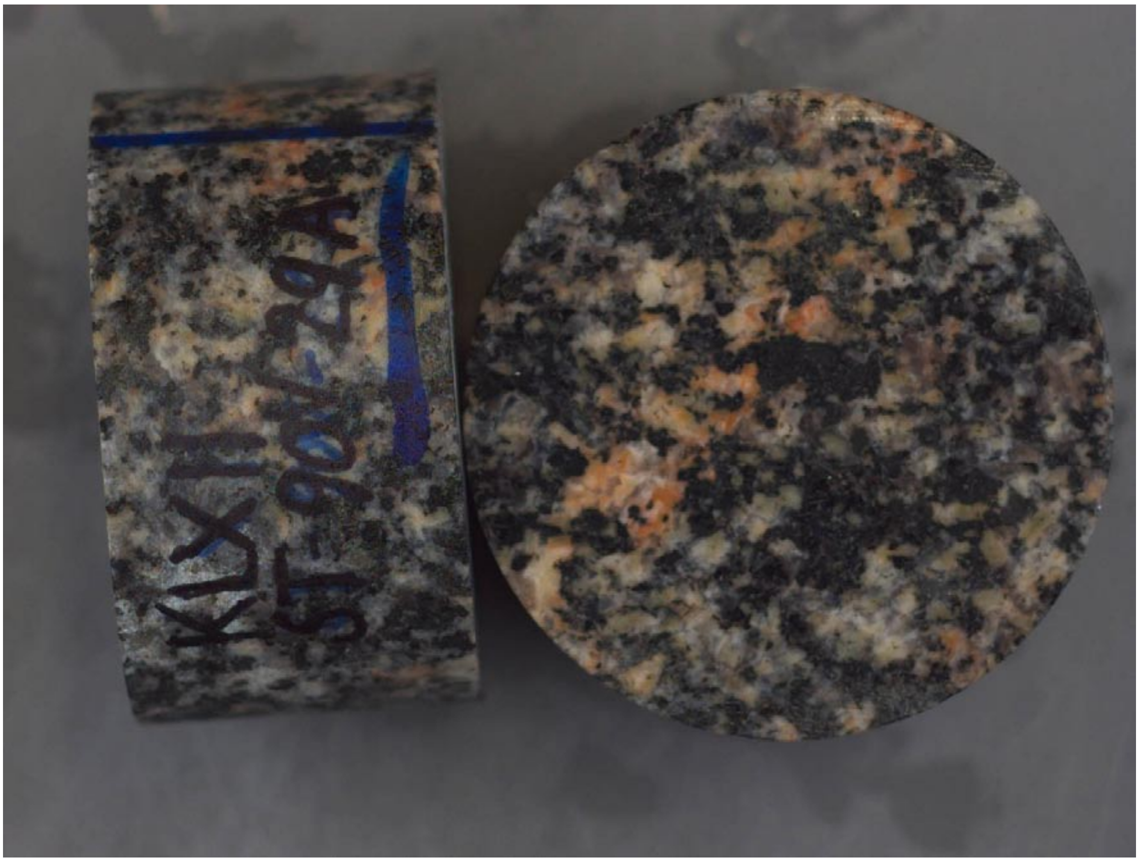

Figure 5-29. *Specimens KLX11ST-90V-29A and B.*

Table 5-57. Porosity, wet and dry density of specimens KLX11ST-90V-29A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-29 Sec low: 451.51	2,780	2,780	0.2

Table 5-58. Thermal properties of specimens KLX11ST-90V-29A and B at ambient temperature, average values, TPS-method.

KLX11ST-90V-29 Sec low: 451.51	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	2.81	1.20	2.34
Standard deviation	0.012	0.018	0.044

Specimens KLX11ST-90V-30A and B

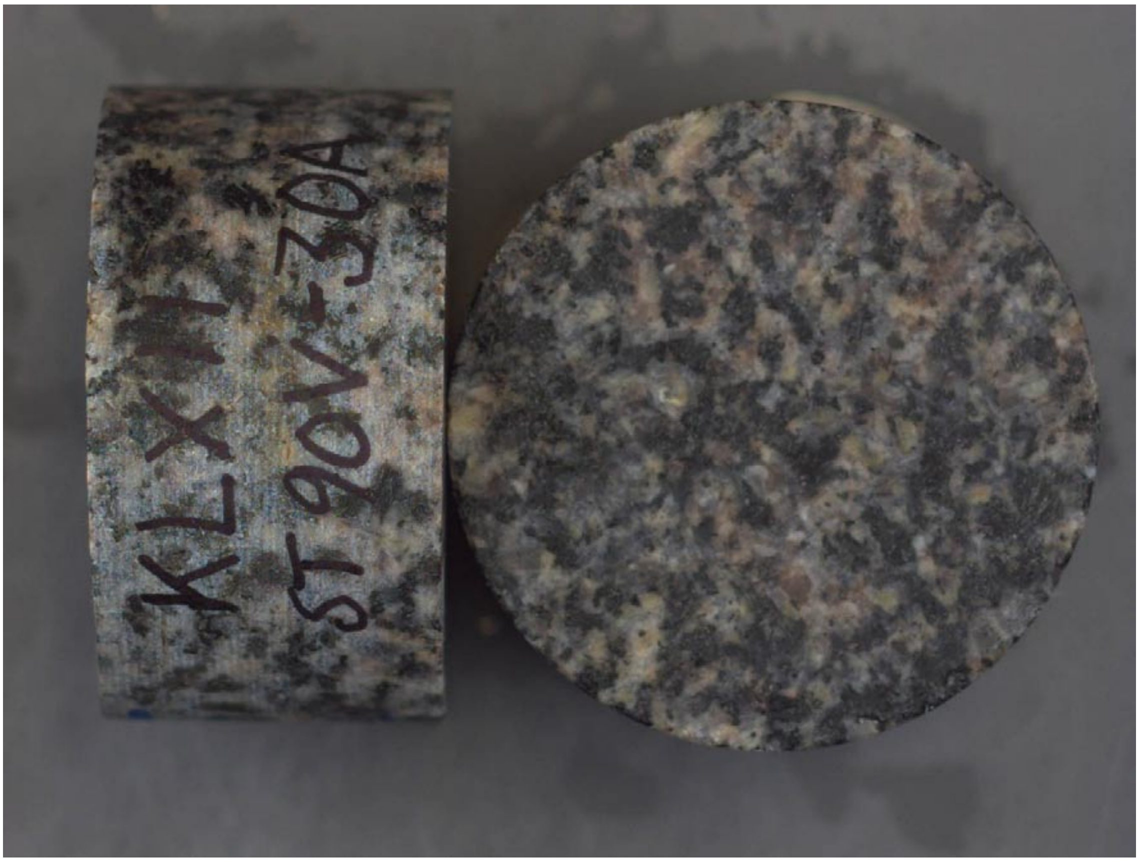

Figure 5-30. *Specimens KLX11ST-90V-30A and B.*

Table 5-59. Porosity, wet and dry density of specimens KLX11ST-90V-30A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-30 Sec low: 452.85	2,780	2,770	0.3

Table 5-60. Thermal properties of specimens KLX11ST-90V-30A and B at ambient temperature, average values, TPS-method.

KLX11ST-90V-30 Sec low: 452.85	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	2.66	1.20	2.21
Standard deviation	0.005	0.005	0.012

Specimens KLX11ST-90V-31A and B

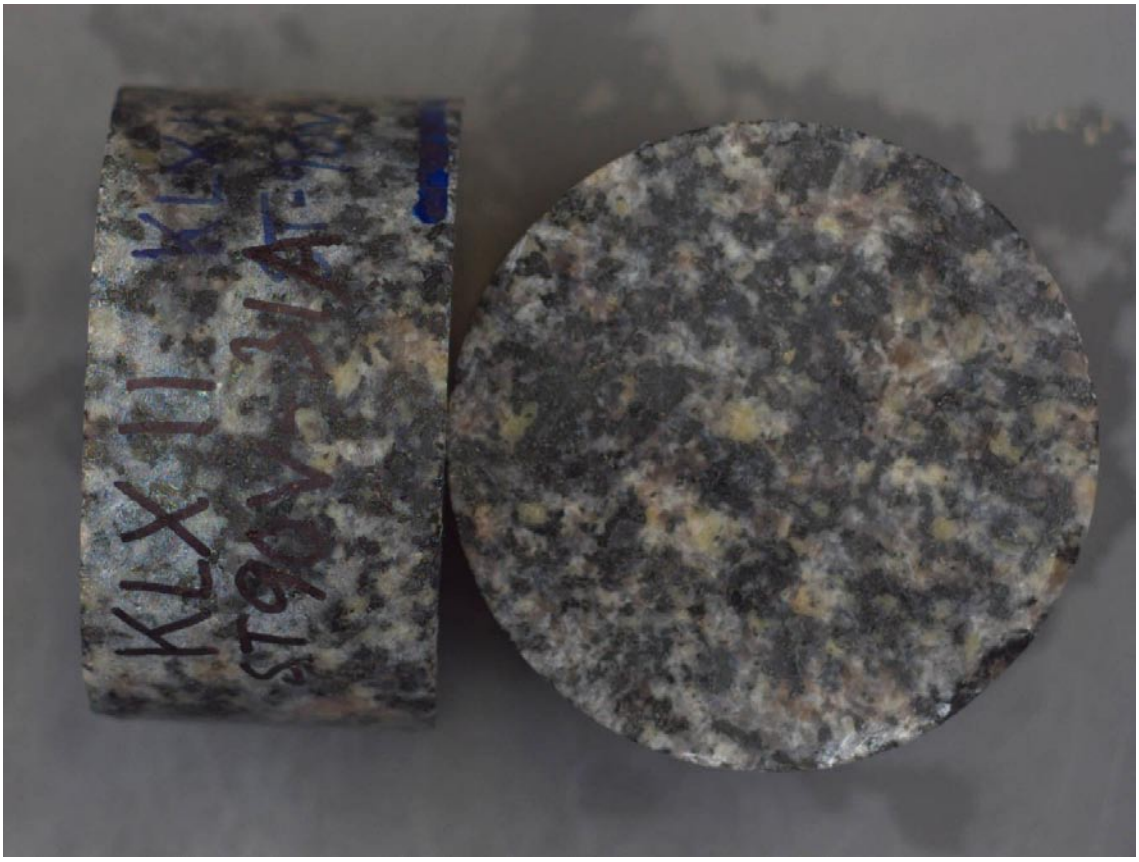

Figure 5-31. *Specimens KLX11ST-90V-31A and B.*

Table 5-61. Porosity, wet and dry density of specimens KLX11ST-90V-31A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-31 Sec low: 463.30	2,780	2,780	0.2

Table 5-62. Thermal properties of specimens KLX11ST-90V-31A and B at ambient temperature, average values, TPS-method.

KLX11ST-90V-31 Sec low: 463.30	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	2.73	1.18	2.32
Standard deviation	0.010	0.015	0.037

Specimens KLX11ST-90V-32A and B

Figure 5-32. *Specimens KLX11ST-90V-32A and B.*

Table 5-63. Porosity, wet and dry density of specimens KLX11ST-90V-32A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-32 Sec low: 486.43	2,740	2,730	0.7

Table 5-64. Thermal properties of specimens KLX11ST-90V-32A and B at ambient temperature, average values.

Sample KLX11ST-90V-32 Sec low: 486.43	TPS method Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]	Calorimeter Calculated heat capacity [MJ/(m³, K)]	Heat capacity [J/(g, K)]
Mean value	2.95	1.34	2.20	2.24	0.819
Standard deviation	0.003	0.007	0.010	–	–

Specimens KLX11ST-90V-33A and B

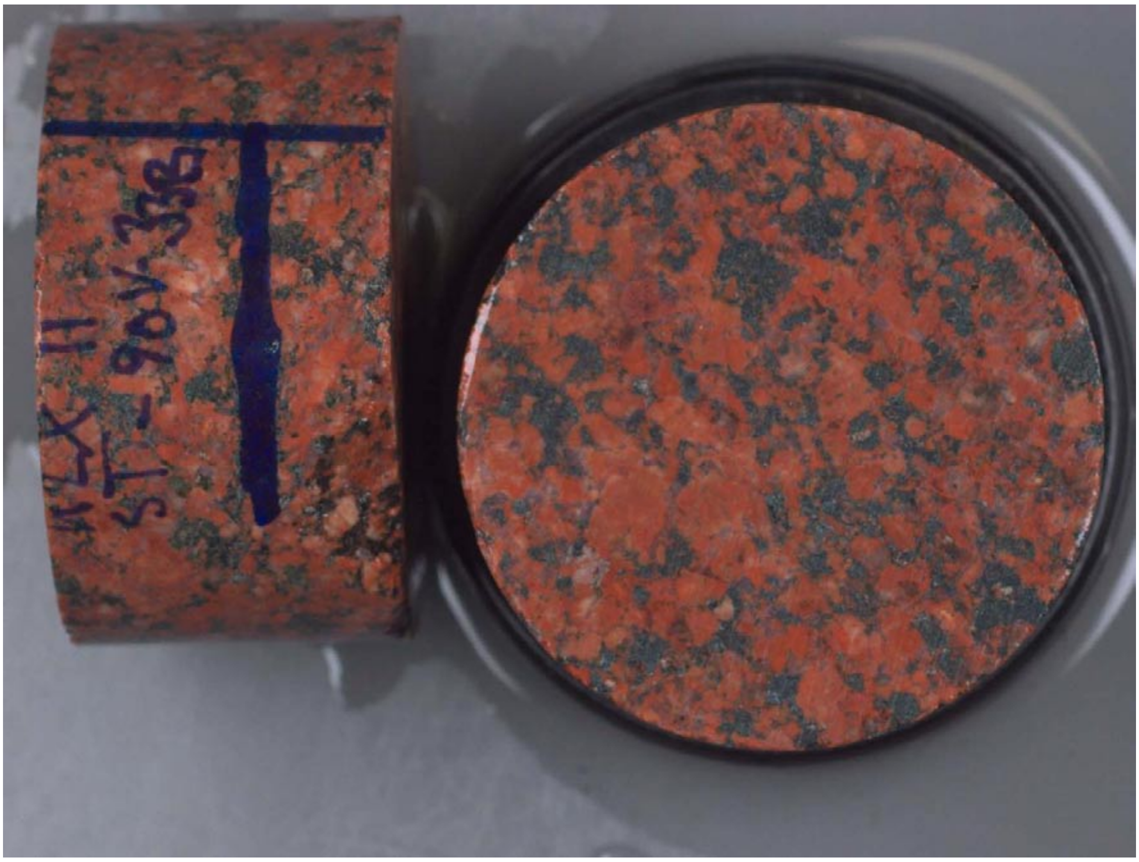

Figure 5-33. *Specimens KLX11ST-90V-33A and B.*

Table 5-65. Porosity, wet and dry density of specimens KLX11ST-90V-33A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-33 Sec low: 490.32	2,690	2,680	1.3

Table 5-66. Thermal properties of specimens KLX11ST-90V-33A and B at ambient temperature, average values, TPS-method.

KLX11ST-90V-33 Sec low: 490.32	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
Mean value	3.07	1.36	2.25
Standard deviation	0.005	0.005	0.011

Specimens KLX11ST-90V-34A and B

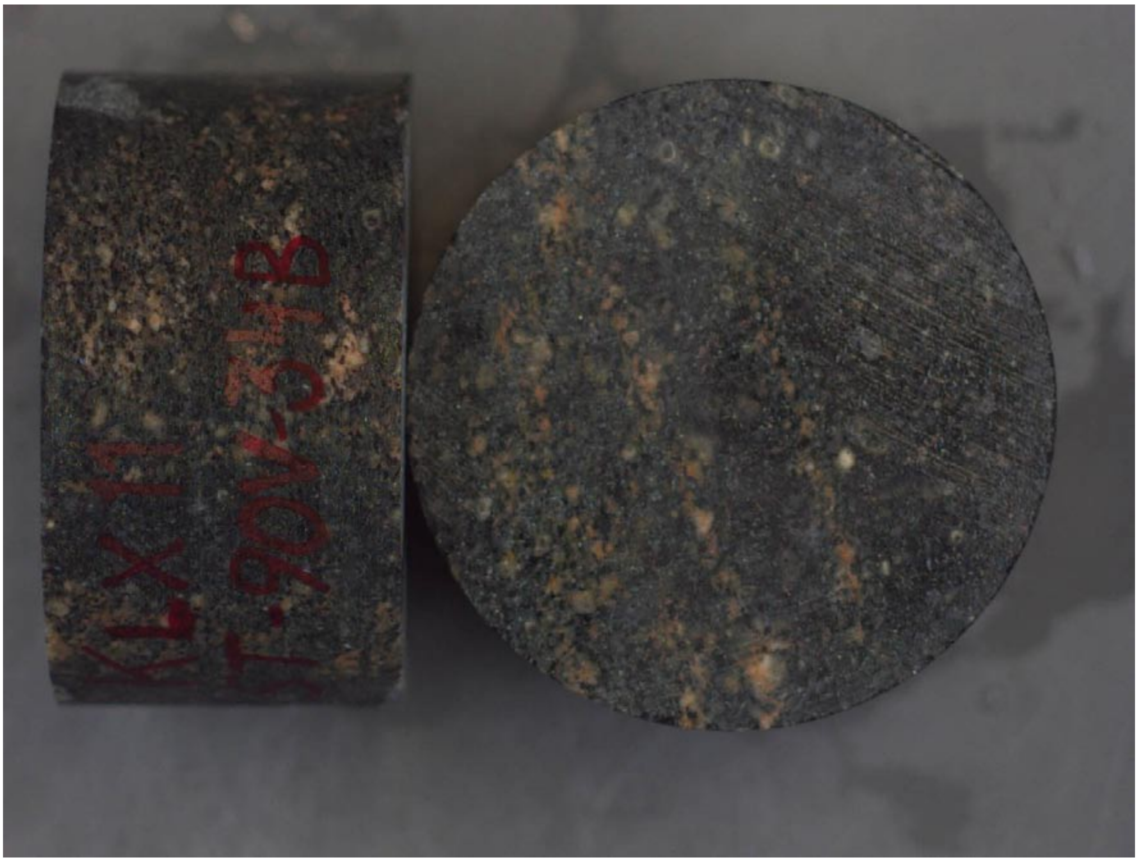

***Figure 5-34.** Specimens KLX11ST-90V-34A and B.*

Table 5-67. Porosity, wet and dry density of specimens KLX11ST-90V-34A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-34 Sec low: 527.22	2,870	2,870	0.2

Table 5-68. Thermal properties of specimens KLX11ST-90V-34A and B at ambient temperature, average values.

Sample KLX11ST-90V-34 Sec low: 527.22	TPS method Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]	Calorimeter Calculated heat capacity [MJ/(m³, K)]	Heat capacity [J/(g, K)]
Mean value	2.66	1.22	2.17	2.27	0.789
Standard deviation	0.011	0.014	0.032	–	–

Specimens KLX11ST-90V-35A and B

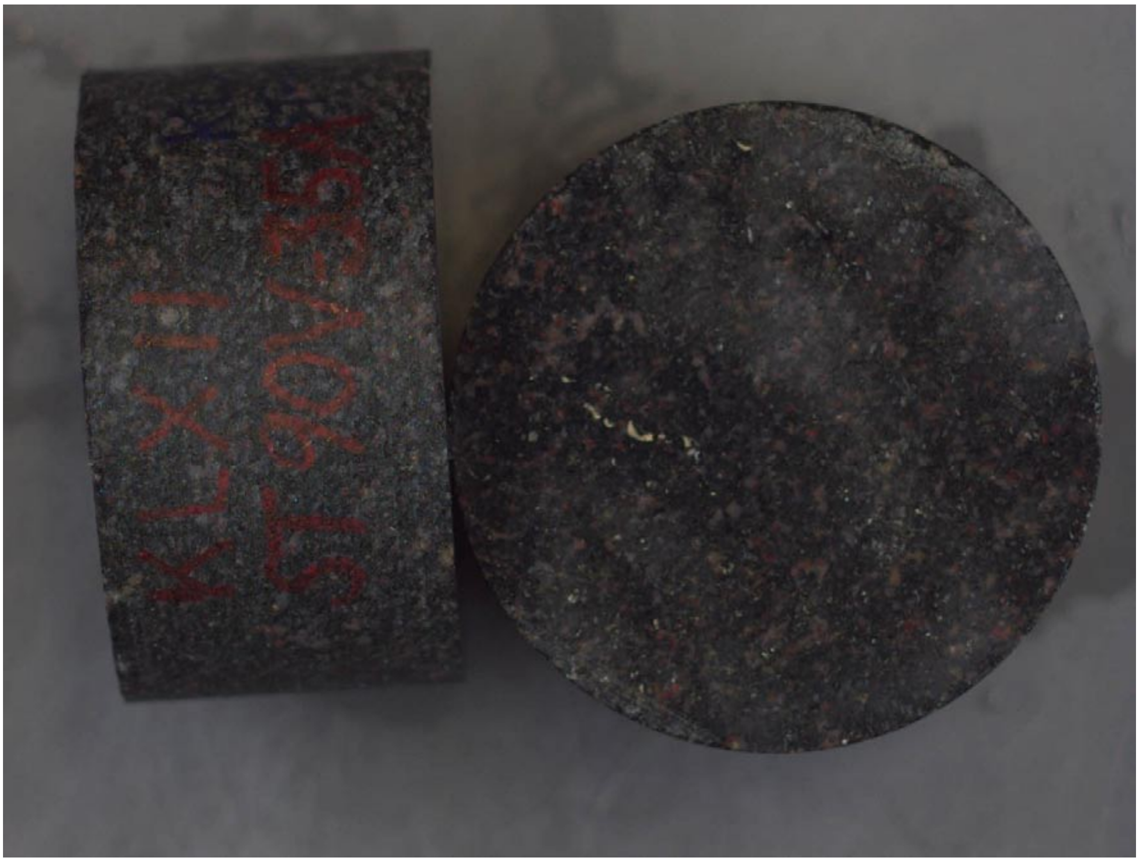

Figure 5-35. *Specimens KLX11ST-90V-35A and B.*

Table 5-69. Porosity, wet and dry density of specimens KLX11ST-90V-35A and B, average values.

Sample	Density, wet [kg/m³]	Density, dry [kg/m³]	Porosity [%]
KLX11ST-90V-35 Sec low: 525.06	2,880	2,870	0.7

Table 5-70. Thermal properties of specimens KLX11ST-90V-35A and B at ambient temperature, average values.

Sample KLX11ST-90V-35 Sec low: 525.06	TPS method Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]	Calorimeter Calculated heat capacity [MJ/(m³, K)]	Heat capacity [J/(g, K)]
Mean value	2.73	1.23	2.22	2.30	0.798
Standard deviation	0.004	0.009	0.020	–	–

5.2 Results for the entire test series

Table 5-71 displays the mean value of five repeated measurements of the thermal properties measured by TPS. Standard deviation is shown in Table 5-72. The results are in both tables grouped according to rock type and borehole.

Table 5-73 displays specific heat capacity of the samples measured by calorimetric method. The specific heat capacity ranged between 0.76 and 0.82 J/(g, K).

The thermal conductivity and thermal diffusivity of specimens measured by TPS representing different depths at 20°C were in the range 2.22–3.48 W/(m, K) respectively 0.97–1.64 mm^2/s. From these results the heat capacity was calculated and appeared to range between 1.87 and 2.56 $MJ/(m^3, K)$. Graphical representations of the heat conductivity and heat capacity versus borehole length of boreholes KLX03, KLX05, KLX07, KLX10 and KLX11 are given in Figure 5-36 and Figure 5-37.

Table 5-71. Mean value of thermal properties of samples at 20°C.

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [$MJ/(m^3, K)$]
KLX03 (501044)			
KLX03ST-90V-1	2.24	0.97	2.31
KLX03ST-90V-2	2.56	1.16	2.20
KLX03ST-90V-3	2.22	0.97	2.30
Average of rock type	**2.34**	**1.03**	**2.27**
KLX07 (501044)			
KLX07ST-90V-4	3.17	1.52	2.09
KLX07ST-90V-5	3.10	1.64	1.89
KLX07ST-90V-6	3.48	1.48	2.35
KLX07ST-90V-7	3.26	1.52	2.14
KLX07ST-90V-8	3.05	1.49	2.04
Average of rock type	**3.21**	**1.53**	**2.10**
KLX10 (501044)			
KLX10ST-90V-9	3.28	1.55	2.12
KLX10ST-90V-10	3.39	1.53	2.21
KLX10ST-90V-11	3.02	1.53	1.98
KLX10ST-90V-12	2.52	1.18	2.14
KLX10ST-90V-13	2.59	1.38	1.87
KLX10ST-90V-14	2.52	1.26	1.99
Average of rock type	**2.89**	**1.41**	**2.05**
KLX05 (501036)			
KLX05ST-90V-17	3.24	1.26	2.56
KLX05ST-90V-18	3.30	1.47	2.24
Average of rock type	**3.27**	**1.37**	**2.40**

Table 5-71 continued. Mean value of thermal properties of samples at 20°C.

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
KLX11 (501036)			
KLX11ST-90V-22	2.75	1.15	2.39
KLX11ST-90V-23	2.61	1.22	2.14
KLX11ST-90V-24	2.61	1.23	2.12
KLX11ST-90V-25	2.60	1.23	2.12
KLX11ST-90V-26	2.66	1.25	2.13
KLX11ST-90V-27	2.67	1.24	2.16
KLX11ST-90V-28	2.74	1.27	2.15
KLX11ST-90V-29	2.81	1.20	2.34
KLX11ST-90V-30	2.66	1.20	2.21
KLX11ST-90V-31	2.73	1.18	2.32
KLX11ST-90V-32	2.95	1.34	2.20
KLX11ST-90V-33	3.07	1.36	2.25
Average of rock type	**2.74**	**1.24**	**2.21**
KLX11 (505102)			
KLX11ST-90V-34	2.66	1.22	2.17
KLX11ST-90V-35	2.73	1.23	2.22
Average of rock type	**2.69**	**1.23**	**2.19**

Table 5-72. Standard deviation of measured values at 20°C.

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
KLX03 (501044)			
KLX03ST-90V-1	0.012	0.024	0.050
KLX03ST-90V-2	0.005	0.010	0.021
KLX03ST-90V-3	0.004	0.010	0.023
KLX07 (501044)			
KLX07ST-90V-4	0.006	0.016	0.025
KLX07ST-90V-5	0.028	0.065	0.059
KLX07ST-90V-6	0.006	0.007	0.015
KLX07ST-90V-7	0.018	0.051	0.080
KLX07ST-90V-8	0.007	0.010	0.018
KLX10 (501044)			
KLX10ST-90V-9	0.004	0.009	0.014
KLX10ST-90V-10	0.003	0.003	0.007
KLX10ST-90V-11	0.013	0.037	0.054
KLX10ST-90V-12	0.005	0.007	0.014
KLX10ST-90V-13	0.013	0.033	0.050
KLX10ST-90V-14	0.005	0.006	0.014
KLX05 (501036)			
KLX05ST-90V-17	0.006	0.003	0.012
KLX05ST-90V-18	0.008	0.016	0.029

Table 5-72 continued. Standard deviation of measured values at 20°C.

Sample identification	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
KLX11 (501036)			
KLX11ST-90V-22	0.006	0.004	0.010
KLX11ST-90V-23	0.005	0.006	0.014
KLX11ST-90V-24	0.005	0.008	0.017
KLX11ST-90V-25	0.004	0.004	0.009
KLX11ST-90V-26	0.006	0.007	0.016
KLX11ST-90V-27	0.004	0.022	0.041
KLX11ST-90V-28	0.009	0.010	0.024
KLX11ST-90V-29	0.012	0.018	0.044
KLX11ST-90V-30	0.005	0.005	0.012
KLX11ST-90V-31	0.010	0.015	0.037
KLX11ST-90V-32	0.003	0.007	0.010
KLX11ST-90V-33	0.005	0.005	0.011
KLX11 (505102)			
KLX11ST-90V-34	0.011	0.014	0.032
KLX11ST-90V-35	0.004	0.009	0.020

Table 5-73. Specific heat capacity measured by calorimeter.

Sample identification	Specific heat capacity [J/(g, K)]	Calculated volumetric heat capacity [MJ/(m³, K)]
KLX03 (501044)		
KLX03ST-90V-1	0.777	2.17
KLX03ST-90V-2	0.762	2.10
KLX07 (501044)		
KLX07ST-90V-5	0.780	2.10
KLX10 (501044)		
KLX10ST-90V-9	0.800	2.13
KLX10ST-90V-12	0.780	2.12
KLX10ST-90V-14	0.777	2.12
KLX05 (501036)		
KLX05ST-90V-15	0.814	2.38
KLX05ST-90V-16	0.814	2.46
KLX05ST-90V-17	0.804	2.33
KLX10 (501044)		
KLX10ST-90V-19	0.805	2.16
KLX10ST-90V-20	0.797	2.14
KLX10ST-90V-21	0.790	2.11
KLX11 (501036)		
KLX11ST-90V-32	0.819	2.24
KLX11 (505102)		
KLX11ST-90V-34	0.789	2.27
KLX11ST-90V-35	0.798	2.30

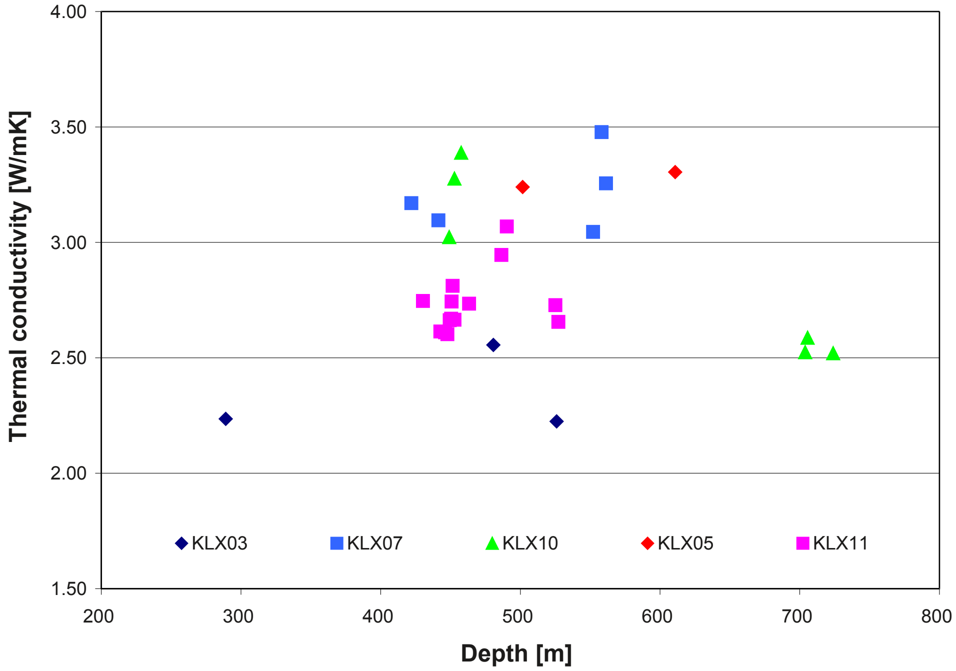

Figure 5-36. *Thermal conductivity versus length of boreholes KLX03, KLX05, KLX07, KLX10 and KLX11 measured with TPS method.*

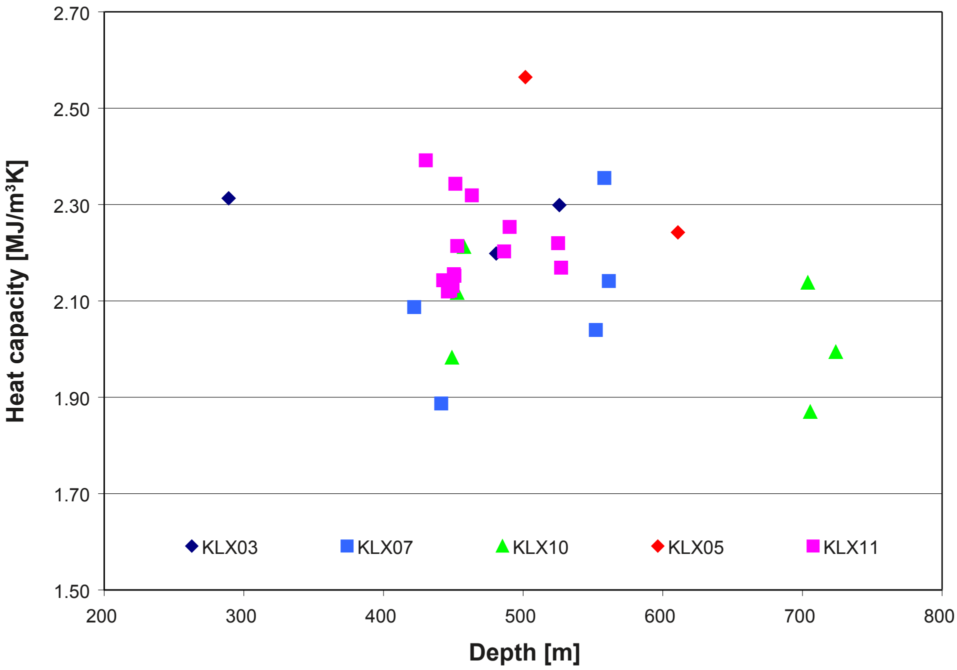

Figure 5-37. *Heat capacity versus length of boreholes KLX03, KLX05, KLX07, KLX10 and KLX11 measured with TPS method.*

6 References

/1/ **SKB, 2001.** Site investigations. Investigation methods and general execution programme. SKB TR-01-29, Svensk Kärnbränslehantering AB.

/2/ **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.

/3/ **Liedberg L, 2007.** Oskarshamn site investigation. Borehole KLX03, KLX05, KLX07A, KLX10 and KLX11A. Determination of porosity by water saturation and density by buoyancy technique. SKB P-report P-07-61. Svensk Kärnbränslehantering AB.

/4/ **SP-metod 4221.** Bestämning av specifik värmekapacitet med en kalorimetrisk metod.

/5/ **Instruction Manual Hot Disc Thermal Constants Analyser Windows 95 Version 5.0, 2001.**

/6/ **ISRM, 1979**. ISRM 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 1.5	
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:	13.45 W/(m. K)	± 0.06%
Thermal Diffusivity:	3.530 mm^2/s	± 0.13%
Heat Capacity:	3.810 MJ/(m^3. K)	± 0.15%

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

Borås 14/08 2006

Patrik Nilsson

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)]
KLX03ST-90V-1			
1	2.25	1.00	2.24
2	2.22	0.96	2.32
3	2.24	0.98	2.29
4	2.24	0.95	2.37
5	2.22	0.95	2.34
KLX03ST-90V-2			
1	2.55	1.16	2.20
2	2.56	1.15	2.23
3	2.56	1.16	2.20
4	2.55	1.18	2.17
5	2.56	1.17	2.19
KLX03ST-90V-3			
1	2.23	0.95	2.33
2	2.22	0.97	2.29
3	2.23	0.98	2.27
4	2.23	0.96	2.31
5	2.23	0.97	2.29
KLX07ST-90V-4			
1	3.18	1.50	2.12
2	3.17	1.51	2.10
3	3.18	1.53	2.08
4	3.17	1.52	2.08
5	3.16	1.54	2.05
KLX07ST-90V-5			
1	3.14	1.75	1.79
2	3.10	1.61	1.93
3	3.09	1.63	1.89
4	3.07	1.63	1.88
5	3.08	1.58	1.94
KLX07ST-90V-6			
1	3.47	1.48	2.35
2	3.48	1.47	2.37
3	3.48	1.48	2.35
4	3.47	1.49	2.34
5	3.49	1.47	2.37

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

Measurement number	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Heat capacity [$MJ/(m^3, K)$]
KLX07ST-90V-7			
1	3.23	1.55	2.09
2	3.27	1.47	2.22
3	3.25	1.59	2.05
4	3.27	1.47	2.23
5	3.25	1.53	2.13
KLX07ST-90V-8			
1	3.04	1.50	2.03
2	3.04	1.50	2.02
3	3.06	1.48	2.07
4	3.05	1.49	2.04
5	3.05	1.50	2.03
KLX10ST-90V-9			
1	3.28	1.54	2.13
2	3.27	1.54	2.12
3	3.28	1.55	2.11
4	3.27	1.56	2.09
5	3.28	1.54	2.13
KLX10ST-90V-10			
1	3.39	1.53	2.21
2	3.39	1.53	2.22
3	3.39	1.54	2.21
4	3.39	1.53	2.21
5	3.39	1.53	2.21
KLX10ST-90V-11			
1	3.02	1.51	2.00
2	3.02	1.56	1.94
3	3.04	1.51	2.01
4	3.03	1.48	2.05
5	3.00	1.57	1.92
KLX10ST-90V-12			
1	2.52	1.19	2.12
2	2.53	1.17	2.15
3	2.52	1.18	2.15
4	2.53	1.18	2.14
5	2.53	1.19	2.13
KLX10ST-90V-13			
1	2.58	1.40	1.84
2	2.59	1.39	1.86
3	2.58	1.42	1.81
4	2.61	1.35	1.94
5	2.57	1.35	1.90

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

Measurement number	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
KLX10ST-90V-14			
1	2.52	1.27	1.98
2	2.53	1.26	2.01
3	2.53	1.26	2.01
4	2.52	1.27	1.99
5	2.51	1.27	1.98
KLX05ST-90V-17			
1	3.23	1.27	2.55
2	3.24	1.26	2.56
3	3.24	1.26	2.57
4	3.24	1.26	2.57
5	3.25	1.26	2.57
KLX05ST-90V-18			
1	3.30	1.49	2.21
2	3.30	1.47	2.25
3	3.32	1.45	2.29
4	3.30	1.48	2.24
5	3.30	1.48	2.23
KLX11ST-90V-22			
1	2.74	1.15	2.39
2	2.75	1.14	2.41
3	2.75	1.15	2.40
4	2.75	1.15	2.38
5	2.75	1.15	2.39
KLX11ST-90V-23			
1	2.61	1.22	2.13
2	2.61	1.22	2.14
3	2.61	1.22	2.13
4	2.61	1.22	2.15
5	2.62	1.21	2.17
KLX11ST-90V-24			
1	2.60	1.23	2.11
2	2.61	1.23	2.12
3	2.62	1.22	2.15
4	2.61	1.23	2.11
5	2.61	1.24	2.11
KLX11ST-90V-25			
1	2.60	1.23	2.11
2	2.60	1.22	2.13
3	2.61	1.23	2.13
4	2.61	1.22	2.13
5	2.60	1.23	2.11

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

Measurement number	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
KLX11ST-90V-26			
1	2.66	1.25	2.12
2	2.67	1.25	2.14
3	2.66	1.25	2.14
4	2.66	1.26	2.11
5	2.67	1.24	2.15
KLX11ST-90V-27			
1	2.66	1.27	2.09
2	2.67	1.24	2.15
3	2.67	1.22	2.20
4	2.67	1.23	2.18
5	2.67	1.23	2.16
KLX11ST-90V-28			
1	2.73	1.29	2.12
2	2.75	1.27	2.16
3	2.74	1.28	2.13
4	2.75	1.27	2.17
5	2.75	1.26	2.18
KLX11ST-90V-29			
1	2.80	1.21	2.32
2	2.82	1.19	2.36
3	2.79	1.22	2.28
4	2.82	1.18	2.40
5	2.82	1.20	2.35
KLX11ST-90V-30			
1	2.66	1.21	2.20
2	2.66	1.20	2.21
3	2.66	1.21	2.21
4	2.67	1.20	2.23
5	2.67	1.20	2.22
KLX11ST-90V-31			
1	2.72	1.20	2.27
2	2.74	1.16	2.36
3	2.73	1.19	2.30
4	2.74	1.18	2.33
5	2.74	1.17	2.34
KLX11ST-90V-32			
1	2.95	1.35	2.19
2	2.94	1.33	2.21
3	2.95	1.33	2.21
4	2.94	1.33	2.21
5	2.95	1.34	2.20

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

Measurement number	Conductivity [W/(m, K)]	Diffusivity [mm²/s]	Heat capacity [MJ/(m³, K)]
KLX11ST-90V-33			
1	3.06	1.36	2.25
2	3.07	1.36	2.26
3	3.07	1.36	2.25
4	3.07	1.37	2.24
5	3.08	1.36	2.27
KLX11ST-90V-34			
1	2.64	1.24	2.13
2	2.65	1.23	2.15
3	2.66	1.21	2.20
4	2.66	1.23	2.16
5	2.67	1.21	2.21
KLX11ST-90V-35			
1	2.73	1.24	2.20
2	2.73	1.21	2.25
3	2.72	1.23	2.21
4	2.73	1.23	2.21
5	2.73	1.23	2.22

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
KLX03ST-90V-1			
1	20	0.48	58–196
2	20	0.46	53–198
3	20	0.43	65–181
4	20	0.46	83–200
5	20	0.46	77–200
KLX03ST-90V-2			
1	20	0.56	70–200
2	20	0.56	28–200
3	20	0.56	32–200
4	20	0.55	36–193
5	20	0.57	22–200
KLX03ST-90V-3			
1	20	0.46	83–200
2	20	0.47	94–200
3	20	0.40	45–168
4	20	0.46	57–198
5	20	0.46	49–195
KLX07ST-90V-4			
1	20	0.73	80–200
2	20	0.73	77–200
3	20	0.71	67–193
4	20	0.74	72–200
5	20	0.74	69–199
KLX07ST-90V-5			
1	20	0.85	85–200
2	20	0.78	69–200
3	20	0.79	91–200
4	20	0.79	97–200
5	20	0.77	88–200
KLX07ST-90V-6			
1	20	0.72	53–200
2	20	0.71	71–200
3	20	0.72	30–200
4	20	0.72	60–200
5	20	0.71	36–200

Table C-1 continued. 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
KLX07ST-90V-7			
1	20	0.75	74–200
2	20	0.72	94–200
3	20	0.72	75–186
4	20	0.71	94–200
5	20	0.74	88–200
KLX07ST-90V-8			
1	20	0.73	75–200
2	20	0.73	84–200
3	20	0.72	85–200
4	20	0.72	75–200
5	20	0.73	86–200
KLX10ST-90V-9			
1	20	0.75	70–200
2	20	0.75	61–200
3	20	0.75	70–200
4	20	0.76	79–200
5	20	0.75	66–200
KLX10ST-90V-10			
1	20	0.74	24–200
2	20	0.74	25–200
3	20	0.75	24–200
4	20	0.74	32–200
5	20	0.74	27–200
KLX10ST-90V-11			
1	20	0.73	81–200
2	20	0.73	55–193
3	20	0.73	68–200
4	20	0.70	93–195
5	20	0.76	69–200
KLX10ST-90V-12			
1	20	0.58	33–200
2	20	0.57	30–200
3	20	0.57	20–200
4	20	0.57	24–200
5	20	0.57	31–198
KLX10ST-90V-13			
1	20	0.68	83–200
2	20	0.68	79–200
3	20	0.69	80–200
4	20	0.65	69–200
5	20	0.55	22–167

Table C-1 continued. 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
KLX10ST-90V-14			
1	20	0.59	37–192
2	20	0.61	40–200
3	20	0.61	43–200
4	20	0.61	37–200
5	20	0.62	42–200
KLX05ST-90V-17			
1	20	0.62	44–200
2	20	0.61	42–200
3	20	0.61	44–200
4	20	0.61	46–198
5	20	0.61	43–200
KLX05ST-90V-18			
1	20	0.73	77–200
2	20	0.71	56–200
3	20	0.70	61–200
4	20	0.72	44–200
5	20	0.72	51–200
KLX11ST-90V-22			
1	20	0.56	57–200
2	20	0.55	65–200
3	20	0.56	61–200
4	20	0.56	56–200
5	20	0.56	71–200
KLX11ST-90V-23			
1	20	0.59	71–200
2	20	0.59	70–200
3	20	0.59	70–200
4	20	0.59	71–200
5	20	0.59	77–200
KLX11ST-90V-24			
1	20	0.60	42–200
2	20	0.60	36–200
3	20	0.59	22–200
4	20	0.60	36–200
5	20	0.59	63–197
KLX11ST-90V-25			
1	20	0.59	47–199
2	20	0.58	48–197
3	20	0.59	42–197
4	20	0.59	45–199
5	20	0.60	43–200

Table C-1 continued. 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
KLX11ST-90V-26			
1	20	0.61	37–200
2	20	0.61	19–200
3	20	0.61	35–200
4	20	0.61	36–200
5	20	0.60	28–200
KLX11ST-90V-27			
1	20	0.62	92–200
2	20	0.60	77–200
3	20	0.55	45–188
4	20	0.60	66–200
5	20	0.60	56–200
KLX11ST-90V-28			
1	20	0.61	35–196
2	20	0.62	44–200
3	20	0.62	34–200
4	20	0.61	46–200
5	20	0.61	47–200
KLX11ST-90V-29			
1	20	0.59	60–200
2	20	0.58	59–200
3	20	0.59	64–200
4	20	0.57	69–199
5	20	0.58	65–200
KLX11ST-90V-30			
1	20	0.59	56–200
2	20	0.58	64–197
3	20	0.58	44–198
4	20	0.57	30–197
5	20	0.58	40–198
KLX11ST-90V-31			
1	20	0.57	63–195
2	20	0.56	66–200
3	20	0.57	64–197
4	20	0.55	39–193
5	20	0.56	63–198
KLX11ST-90V-32			
1	20	0.65	66–200
2	20	0.65	60–200
3	20	0.65	62–200
4	20	0.65	64–200
5	20	0.65	63–200

Table C-1 continued. 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
KLX11ST-90V-33			
1	20	0.66	51–200
2	20	0.66	59–200
3	20	0.66	65–200
4	20	0.66	55–200
5	20	0.66	67–200
KLX11ST-90V-34			
1	20	0.60	54–200
2	20	0.57	47–190
3	20	0.59	51–200
4	20	0.60	58–200
5	20	0.58	52–198
KLX11ST-90V-35			
1	20	0.60	29–200
2	20	0.59	35–200
3	20	0.57	21–192
4	20	0.60	37–200
5	20	0.60	31–200

Appendix D

Table D-1. Modal analyses of thin sections of specimens from KLX05, KLX07A, KLX10 and KLX11A

Sample Id	Sec low	Quartz	Kvarts Feldspar	Plagioclase	Biotite	Muscovite	Chlorite	Epidote	Titanite	Calcite	Amphibole	Opaque	Apatite	Clinopyroxene
KLX07ST-200-1	559.85	24.4	22.4	43.2	6.4	–	–	2.2	0.2	0.2	–	1	–	–
KLX07ST-200-2	553.68	24.8	25.2	40.2	7.2	–	–	1.2	0.6	0.2	–	0.6	–	–
KLX10ST-200-3	455.05	25.4	24.2	38.6	8.6	–	–	1.6	1.2	0.2	–	0.2	–	–
KLX10ST-200-4	707.04	8.8	11.6	63.8	8.2	–	–	3.2	0.8	–	2.2	0.4	1	–
KLX05ST-200-5	408.40	6.4	–	23.2	17.4	0.4	6.2	–	0.2	–	38.0	2.2	0.2	5.0
KLX05ST-200-6	371.73	9.8	–	25.6	15.6	–	1.4	–	–	–	16.2	3.6	–	26.4
KLX05ST-200-7	361.31	8.6	–	3.6	13	–	1.4	–	–	–	14.4	5	–	51
KLX05ST-200-8	502.89	8.6	–	48	9.2	–	1.2	2	0.4	–	30.0	0.6	–	–
KLX11ST-200-9	527.03	11.6	–	51.8	10.2	–	–	1.8	2	0.4	20.4	1.6	–	–
KLX11ST-200-10	524.87	15	–	32.6	19.4	–	–	–	–	–	32.0	0.8	0.2	–