Report
P-21-07
December 2021

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SVENSK KÄRNBRÄNSLEHANTERING

ISSN 1651-4416
SKB P-21-07
ID 1898009
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Keywords: Thermal properties, Thermal conductivity, Thermal diffusivity, Heat capacity, Transient plane source method, Elasticity parameters, Indirect tensile strength, Tension test, Strain measurement, AP SFK-21-006.

Abstract

The density, thermal and mechanical properties were determined on water-saturated specimens from borehole KFM24 in the Forsmark site investigation area. The rock type was granite to granodiorite (101057). All specimens had a more or less foliated rock structure. The cores were sampled from depths ranging between 65–526 m.

The specimens were water-saturated using tap water and all subsequent measurements were conducted at this moisture condition. The density was determined on 25 specimens followed by measuring the thermal properties of 9 pairs of specimens. The thermal conductivity and diffusivity were measured and the volumetric heat capacity was calculated from the thermal conductivity and diffusivity. The testing ended with 21 indirect tensile tests yielding the indirect tensile strength. The strain was measured using strain gauges during the indirect tensile tests. The density at a water-saturated condition was 2 648–2 694 kg/m^3.

Thermal properties were measured at ambient temperature (23°C) and under water-saturated conditions. The determination of the thermal properties is based on a direct measurement method, the so called "Transient Plane Source Method" (TPS).

Thermal conductivity and thermal diffusivity at 23°C were in the range of 3.1–3.8 W/(m, K) and 1.8–2.0 mm^2/s, respectively. The volumetric heat capacity, which was calculated from the thermal conductivity and diffusivity, ranged between 1.8 and 2.3 MJ/(m^3, K).

The indirect tensile tests were conducted with the diametrical compression across the foliation planes. The indirect tensile strength was in the range 9.7–16.5 MPa.

Sammanfattning

Densiteten, termiska och mekaniska egenskaper har bestämts på vattenmättade prover från borrhål KFM24 i Forsmarks platsundersökningsområde. Bergarten i samtliga prover är granit till granodiorit (101057). Samtliga prover hade en mer eller mindre folierad bergstruktur. Proverna har tagits på djupnivåer mellan 65–526 m.

Proverna vattenmättades med kranvatten och alla efterföljande mätningar gjordes vid denna fukthalt. Densiteten mättes på samtliga 25 prover följt av mätning av de termiska egenskaperna på 9 par prover. Termisk konduktivitet och termisk diffusivitet mättes varefter den volumetriska värmekapaciteten beräknades. Provningen avslutades med 21 stycken indirekta test av draghållfastheten som gav den indirekta draghållfastheten. Töjningar mättes med hjälp av trådtöjningsgivare under de indirekta dragförsöken. Densiteten i ett vattenmättat tillstånd var 2 648–2 694 kg/m^3.

Termisk konduktivitet och termisk diffusivitet har bestämts vid rumstemperatur (23 °C) och vattenmättnad. Mätningarna av egenskaperna utfördes med den direkta metoden "Transient Plane Source" (TPS).

Termisk konduktivitet och termisk diffusivitet vid 23 °C bestämdes till 3,1–3,8 W/(m, K) respektive 1,8–2,0 mm^2/s. Den volumetriska värmekapaciteten (produkten av densitet och specifk värmekapacitet), som beräknades från konduktivitet och diffusivitet, varierade mellan 1,8 and 2,3 MJ/(m^3, K).

De indirekta dragförsöken utfördes så att proverna belastades med diametral kompression tvärs foliationsplanen. Den indirekta draghållfastheten var 9,7–16,5 MPa.

Contents

1 Introduction

The spent nuclear fuel from the Swedish nuclear power program will, according to the plans, be handled by deposition in the bedrock occurring at the Forsmark area. To protect humans and the environment on a long-term, SKB has planned to construct a geological repository in the Swedish primary rock. The nuclear waste repository is an important part in the system to handle the spent fuel and its main task is to keep the nuclear waste separated from humans and the environment.

The performance and results of measurements of density, thermal properties and indirect tensile strength on water-saturated drill core specimens are reported in this document. The drill cores originate from the borehole KFM24 which is located within the site investigation area in Forsmark, see map in Figure 1-1. The purpose of borehole KFM24 was to get more detailed knowledge of the rock properties at a planned raise bored shaft close to the borehole.

The borehole is a conventionally drilled cored borehole, with a length of c. 550 m. The rock type of the selected cores is granite to granodiorite (101057).

The tests were carried out in the material and rock mechanics laboratories at the Departments of Applied mechanics, Fire technology, and Infrastructure and concrete at the at RISE Research Institutes of Sweden in Borås.

SKB sent rock cores to RISE which arrived in Borås in November 2020 and were tested during January to March 2021. Additional pre-cut specimens were sent to RISE November 2021 and were tested during December 2021 to April 2022. A planning of how to extract specimens from the cores was first conducted together with SKB and Geosigma. Cylindrical specimens were cut from the cores based on the plan. The end surfaces of the specimens subjected to measurements of thermal properties were grinded in order to comply with the required tolerances. The specimens were water saturated and stored in water for a minimum of 7 days, up to testing. This yields a water saturation which is intended to resemble the in-situ moisture condition. All tests were carried out at this moisture condition. The density was first determined on each specimen followed by the measurement of thermal properties and finally the mechanical tests were conducted.

The method description SKB MD 160.002e was followed for the water saturation and density measurements. The thermal properties, i.e., thermal conductivity and thermal diffusivity, have been determined by using the Transient Plane Source Method (TPS) (Gustafsson 1991). The volumetric heat capacity can be calculated if the density is known. The method description SKB MD 191.001e was followed for the measurement of the thermal properties. The tests also comply to ISO 22007-2:2015 (ISO 2015) except that the specimens are not plastics. The method description SKB MD 190.004e was followed for the sampling and for the indirect tensile strength tests. The method follows ASTM D3967-95a (ASTM 1996) for the indirect tensile strength tests. The tests were carried out with additional measurements of strains by means of strain gauges similar to Jacobsson (2006) and Jacobsson et al. (2016).

The rock material had a foliated structure, which implies that both the thermal and mechanical properties are anisotropic. The foliation direction relative to the core axis differed between the specimens. The thermal measurements were carried out in the axial direction of the specimens. Hence, the properties were measured relative to the foliation angles given by the foliation orientation in the specimens. The loading direction was perpendicular to the foliation at the indirect tensile tests. A line was drawn on each specimen showing the direction of loading. Note that a true loading perpendicular to the foliation would require that the foliation direction must be parallel to the specimen axis, which is not the case here.

The thermal conductivity is assumed isotropic despite the foliated structure according to discussions prior to testing. This will yield a result in between the conductivity in the normal and through-plane directions relative to the foliation.

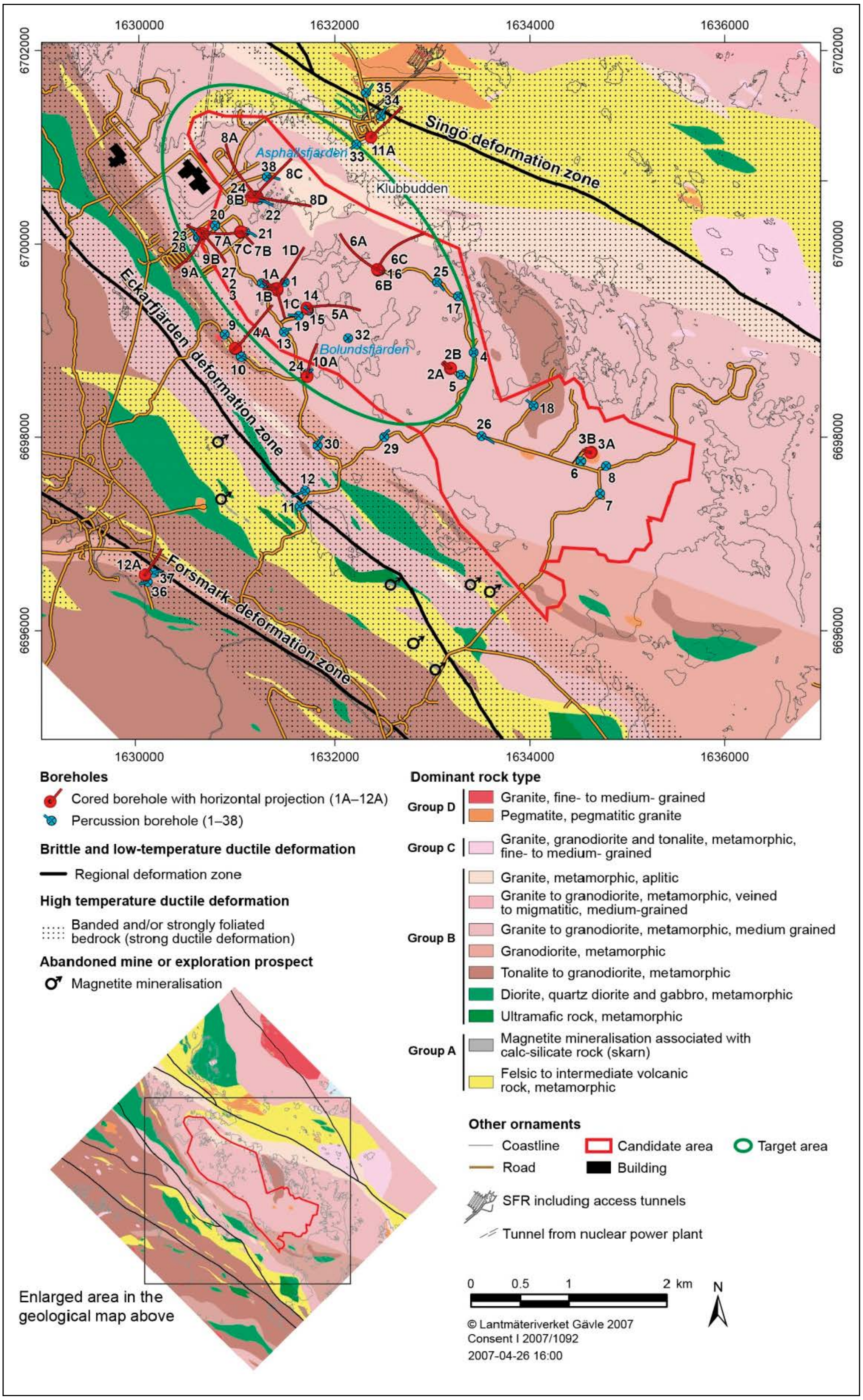


Figure 1-1. *Geological map showing the location of all boreholes drilled up to April 2007 within or close to the Forsmark candidate area. The projection of each borehole on the horizontal plane at top of casing is also shown in the figure. The borehole KFM24, from which the samples to this study were taken, is marked in the map with the number 24. This borehole is located close to a planned vertical shaft down to the central area of the future repository.*

The controlling documents for the activity are listed in Table 1-1. Both Activity Plan and Method Descriptions are SKB's internal controlling documents.

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

Activity plan	Number	Version
Provning av indirekt draghållfasthet och termisk konduktivitet på prover från KFM24	AP SFK-21-006	1.0
Method descriptions	**Number**	**Version**
Determining density and porosity of intact rock	SKB MD 160.002e	3.0
Indirect test of tensile strength	SKB MD 190.004e	3.0
Determining thermal conductivity and thermal capacity	SKB MD 191.001e	3.0

2 Objective

The rock material in the core from KFM24 is albitised to various degrees and it is of interest to investigate whether the results are affected by this degree of alteration. The test program of this contains complementary investigations, and its results increase the database for this version of the rock type 101057, regarding both mechanical and thermal properties. Moreover, a testing work using a field Point Load Tests equipment has been carried out on the same core as in this investigation (KFM24) (Hakami and Winell 2021). To evaluate the results from that study, additional laboratory experiments are needed from the same core sections. In addition, the results are also of interest for the design and construction of the nearby planned shaft.

3 Specimens

The specimens are subjected to measurements of density, thermal and mechanical properties. To distinguish the investigations and to cohere with the method descriptions, different labelling is introduced for the specimens when thermal and mechanical tests are conducted even if they are the same physical specimens.

3.1 Extraction plan

A total of 9 core sectionswere selected for this investigation. A plan for how to extract specimens for the different investigations was made together with SKB staff. The markings of how to extract the specimens from the individual cores including observations of defects for seven of the sections are shown in Figures 3-1 and 3-2. The core parts belonging the two remaining sections were already cut into specimens when they were arrived at RISE.

The rock type characterisation was made according to Stråhle (2001) using the SKB mapping system (Boremap). The labelling and position in the borehole (adjusted secup and adjusted seclow) and the rock type for the individual specimens are shown in Tables 3-1 and 3-2.

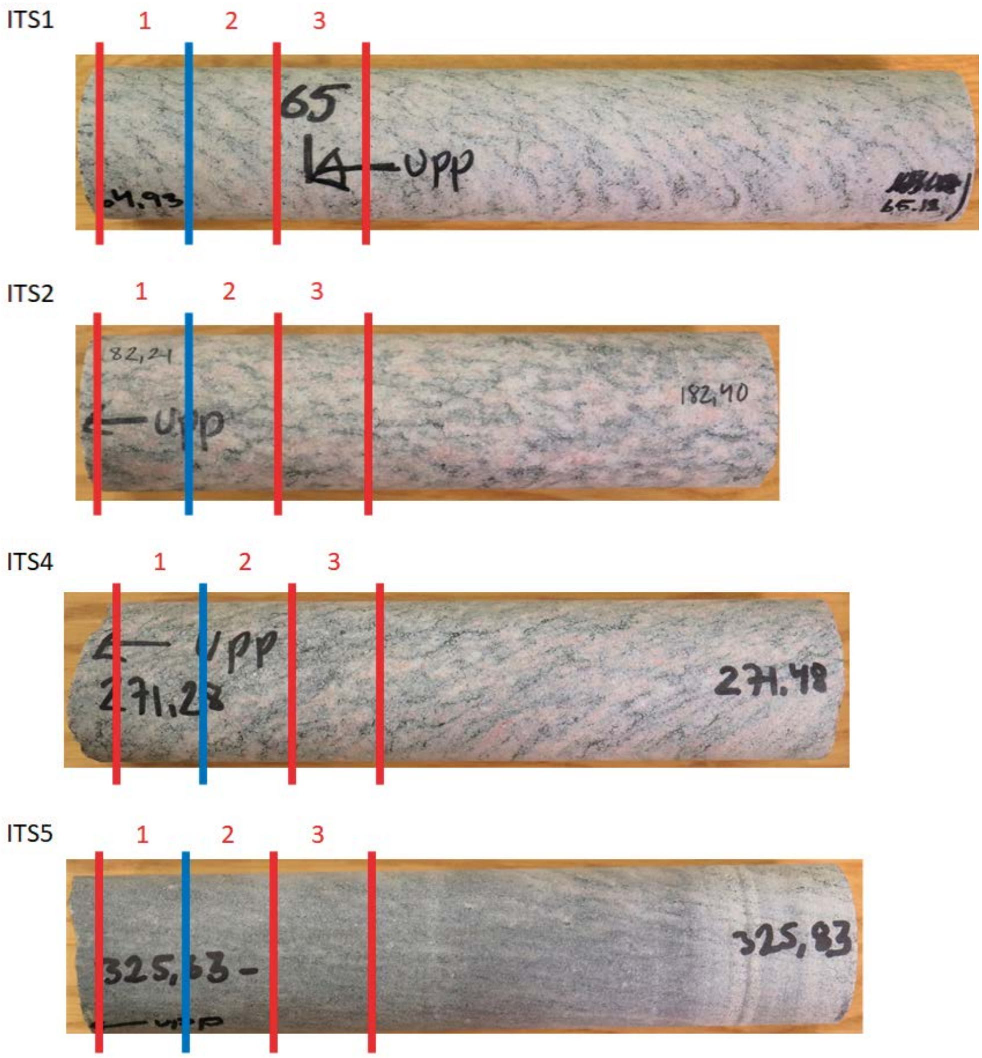


Figure 3-1. *Core and specimen designations and layout for cutting the specimens. The lines show approximate cutting positions. The blue line marks surfaces that were grinded.*

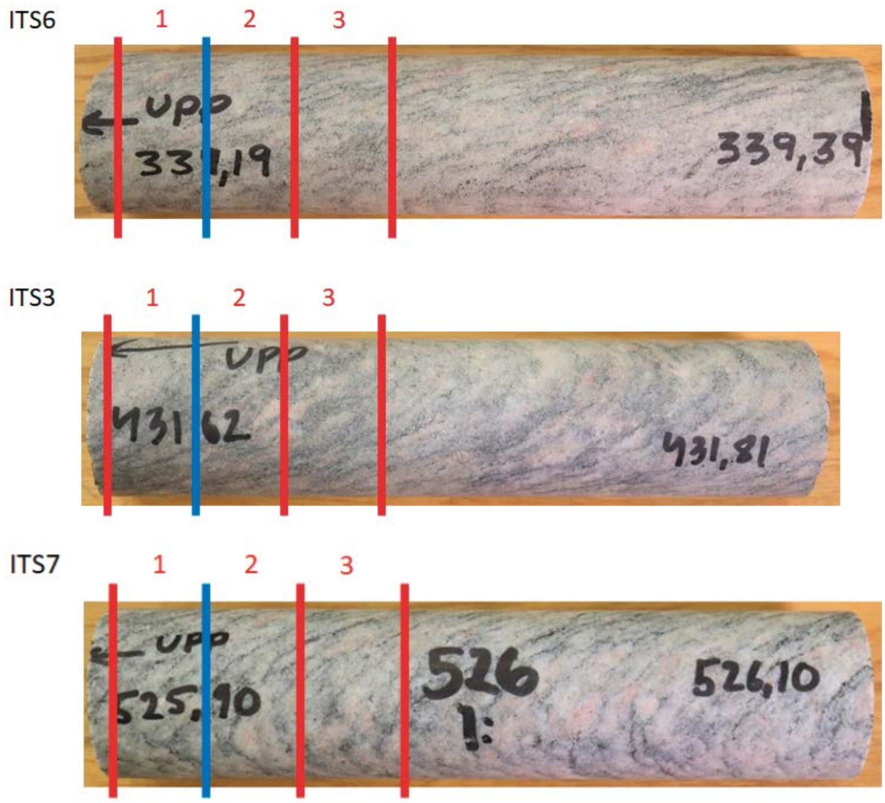


Figure 3-2. *Core and specimen designations and layout for cutting the specimens. The lines show approximate cutting positions. The blue line marks surfaces that were grinded.*

3.2 Specimens for measuring thermal properties

The measurements of thermal properties are made with a thin sensor that is placed between two pieces of rock cores (cf. blue line in Figure 3-1 and 3-2). Two of the extracted specimens are needed for one thermal measurement. Table 3-1 specifies the specimen interfaces where measurements have been conducted. Thus, KFM24-90V-01 is the interface between two parts where the sensor is placed. The upper and lower distance (secup and seclow in Table 3-1) where the properties are probed denotes the distances within which the actual heat wave penetrates and not the physical distance of the specimens.

Table 3-1. Specimen identification, sampling level (borehole length) and rock type for all specimens (based on the Boremap overview mapping).

Identification	Adj Secup (m)	Adj Seclow (m)	Rock type/occurrence	Core-specimen number (cf. Figure 3-1 and 3-2)
KFM24-90V-01	64.95	64.97	Granite to granodiorite (101057)	1-1 and 1-2
KFM24-90V-02	182.24	182.26	Granite to granodiorite (101057)	2-1 and 2-2
KFM24-90V-03	271.31	271.33	Granite to granodiorite (101057)	4-1 and 4-2
KFM24-90V-04	325.66	325.68	Granite to granodiorite (101057)	5-1 and 5-2
KFM24-90V-05	339.22	339.24	Granite to granodiorite (101057)	6-1 and 6-2
KFM24-90V-06	431.65	431.67	Granite to granodiorite (101057)	3-1 and 3-2
KFM24-90V-07	525.93	525.95	Granite to granodiorite (101057)	7-1 and 7-2
KFM24-90V-08	399.73	399.83	Granite to granodiorite (101057)	A and B (*)
KFM24-90V-09	400.53	400.63	Granite to granodiorite (101057)	C and D (*)

(*) Pictures of the specimens are shown in Figures 6-2 and 6-3. No cores were delivered.

3.3 Specimens for indirect tensile tests

A list of 21 specimens for the indirect tensile tests is shown in Table 3-2.

Table 3-2. Specimen identification, sampling level (borehole length) and rock type for all specimens (based on the Boremap overview mapping).

Identification	Adj Secup (m)	Adj Seclow (m)	Rock type/occurrence	Core-specimen number (cf. Figure 3-1 and 3-2)
KFM24-110-01	64.93	64.96	Granite to granodiorite (101057)	1-1
KFM24-110-02	64.96	64.99	Granite to granodiorite (101057)	1-2
KFM24-110-03	64.99	65.02	Granite to granodiorite (101057)	1-3
KFM24-110-04	182.22	182.25	Granite to granodiorite (101057)	2-1
KFM24-110-05	182.25	182.28	Granite to granodiorite (101057)	2-2
KFM24-110-06	182.28	182.31	Granite to granodiorite (101057)	2-3
KFM24-110-07	271.29	271.32	Granite to granodiorite (101057)	4-1
KFM24-110-08	271.32	271.35	Granite to granodiorite (101057)	4-2
KFM24-110-09	271.35	271.38	Granite to granodiorite (101057)	4-3
KFM24-110-10	325.64	325.67	Granite to granodiorite (101057)	5-1
KFM24-110-11	325.67	325.70	Granite to granodiorite (101057)	5-2
KFM24-110-12	325.70	325.73	Granite to granodiorite (101057)	5-3
KFM24-110-13	339.20	339.23	Granite to granodiorite (101057)	6-1
KFM24-110-14	339.23	339.26	Granite to granodiorite (101057)	6-2
KFM24-110-15	339.26	339.29	Granite to granodiorite (101057)	6-3
KFM24-110-16	431.63	431.66	Granite to granodiorite (101057)	3-1
KFM24-110-17	431.66	431.69	Granite to granodiorite (101057)	3-2
KFM24-110-18	431.69	431.72	Granite to granodiorite (101057)	3-3
KFM24-110-19	525.91	525.94	Granite to granodiorite (101057)	7-1
KFM24-110-20	525.94	525.97	Granite to granodiorite (101057)	7-2
KFM24-110-21	525.97	526.00	Granite to granodiorite (101057)	7-3

4 Equipment

4.1 Specimen preparation

A circular saw with a diamond blade was used to cut the specimens to their final lengths. The surfaces were then grinded after cutting in a grinding machine in order to achieve a high-quality surface for the thermal measurements that complies with the required tolerances. The measurements of the specimen dimensions were made with a sliding calliper. Furthermore, the tolerances were checked by means of a dial indicator and a stone face plate. The specimen preparation is carried out in accordance with ASTM (2001).

4.2 Water saturation and density measurement

The following equipment was used for the density and porosity determinations:

- Scale for weight measurement after water saturation (scale routinely checked with reference weight). Measurement accuracy ± 0.002 g.
- Scale for weight measurement after water saturation in surface dry condition (scale routinely checked with reference weight). Measurement accuracy ± 0.02 g.

4.3 Transient plane source

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

- Kapton insulated sensor 5501, with a radius of 6.4 mm. The sensor 5501 fulfils the recommended relation between sensor radius and sample geometry of the samples in ISO 22007-2.
- TPS-apparatus, TPS 2500s, see Figure 4-1 as well as the software Hotdisk Thermal Constants Analyser version 7.4.4.
- Stainless Sample holder and plastic bags around the specimen.

Function control of TPS instrumentation was performed according to BRk-QB-M26-02 (SP quality document), as well as to the accredited standard ISO 22007-2:2015 (ISO 2015).

The experimental set-up is shown in Figure 4-2.

Figure 4-1. *TPS-apparatus TPS 2500s with sensor switch. (The placement of the equipment was changed since the picture was taken)*

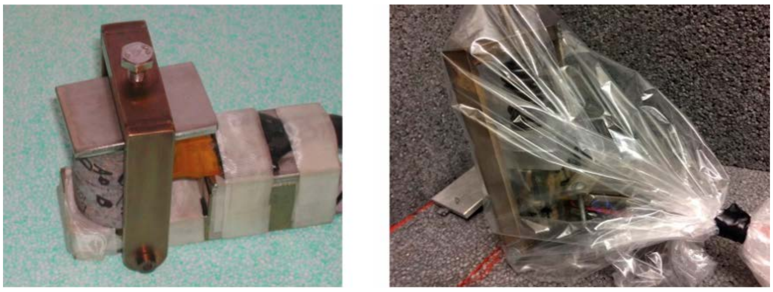


Figure 4-2. *Specimens mounted in stainless sample holder (left), and sample holder with mounted specimens wrapped in plastic (right). (Pictures were taken from an earlier measurement series.)*

4.4 Indirect tensile strength test

The mechanical testing was carried out in a load frame where the crossbar is mechanically driven by screws and has a maximum load capacity of 100 kN in compression. The compressive load was measured by an external 100 kN load cell. The uncertainty of the load measurement is less than 1%.

Strain gauges from Kyowa with a gauge length of 20 mm and 120 ohm resistance were used for the strain measurements. The strain gauges were two-directional, 0 and 90 degrees, and a three-wire connection allowing for temperature compensation was used in all tests. The strain and the load values were sampled using an HBM QuantumX universal data acquisition system.

The frame was equipped with a pair of curved bearing blocks, radius 39 mm and width 29 mm, with pins for guiding the vertical deformation, see Figure 4-3. The top platen includes a spherical seating in order to have a fully centred loading position. The specimens were photographed with a digital camera and the photographs were stored in a jpeg-format.

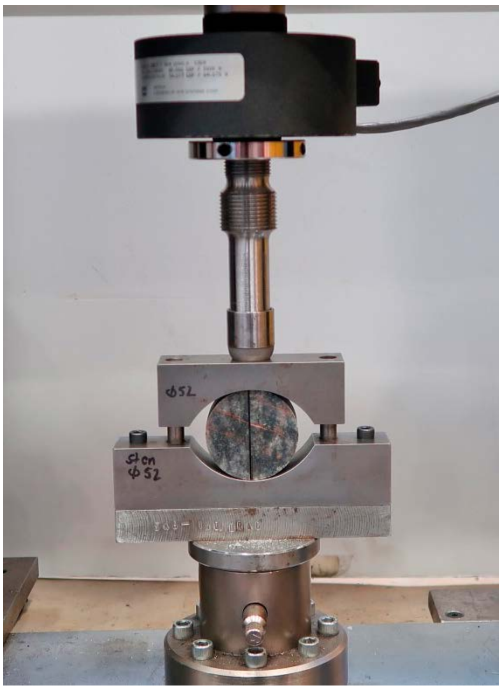


Figure 4-3. *Test-set up for the indirect tensile strength test. The load cell is visible in the top and the curved bearing blocks are seen below that. (The specimen in the picture is from an earlier measurement series.)*

5 Execution

The specimens were going through the following activities which are described in Section 5-1 to 5-5:

1. Cut and grind the specimens.
2. Take photographs of the specimens after the preparation.
3. Water saturation of the specimens for a minimum of 7 days.
4. Measure the wet density at a water-saturated condition.
5. Measure the thermal properties at a water-saturated condition.
6. Measure the mechanical properties at a water-saturated condition.
7. Take photographs of the specimens after the mechanical tests.

5.1 Specimen preparation

The steps for the specimen preparation are shown in Table 5-1.

Table 5-1. Activities during the specimen preparation.

Step	Activity
1	The drill cores were marked where the specimens are to be taken.
2	The specimens were cut to the specified length according to markings and the cutting surfaces were grinded.
3	The tolerances were checked: parallel and perpendicular end surfaces, smooth and straight circumferential surface.
4	The diameter and height were measured three times each. The respective mean value determines the dimensions that are reported.

5.2 Water saturation and density measurement

The water saturation and determination of the density of the wet specimens were made in accordance with the method description SKB MD 160.002e (SKB internal controlling document). This includes the determination of density in accordance with ISRM (1979) and water saturation by EN 13755 (CEN 2008).

The density of the water at the time of the measurements was 998 kg/m^3. The execution procedure followed the description in SKB MD 160.002e, see Table 5-2.

Table 5-2. Activities during the water saturation and density measurements.

Step	Activity
1	The specimens were water saturated using tap water in normal air pressure for at least seven days.
2	The specimens were weighed in tap water. The temperature of the water was measured and the water density was determined from a table.
3	The specimens were surface dried with a towel and weighed.
4	The density at a water-saturated condition was determined.

5.3 Transient plane source

5.3.1 Principle of Transient Plane Source

The principle of the TPS-method is to install a sensor consisting of a thin Nickel double spiral, embedded in an insulation material, between two rock samples. During the measurement, the sensor works both as a heat emitter (a constant electrical power is developed during a certain time) and a heat receptor (the temperature increase of the sensor is measured through the resistivity of the Nickel due to the strong temperature dependence for the resistivity of Nickel). The input data and results of the direct measurement are registered and analysed by the same software and electronics that govern the measurement. The first part of the heating period is ignored to allow for boundary effects in the sensor/specimen interface to vanish. The last part can sometimes also be ignored to ensure that the heat wave do not exceed the diameter of the sensor, according to the measurement standard. The transient temperature evolution on the sensor, ΔT_S, is fitted to the equation of temperature increase of a sensor in a homogeneous, isotropic and semi-infinite material.

$$\Delta T_s(\tau) = P_0\left(\pi^{3/2} r k\right)^{-1} D(\tau),$$

where P_0 is power output of probe, r is the radius of the sensor, k is the thermal conductivity of the material, $\tau = (t/\theta)^{1/2}$, t is time, $\theta = r^2/\alpha$, α is the thermal diffusivity, and $D(\tau)$ is a dimensionless time function defined as:

$$D(\tau) = [m(m+1)]^{-2} \int_0^{\tau} \sigma^{-2} \left[\sum_{i=1}^{m} i \sum_{j=2}^{m} j \exp\left(\frac{-(i^2+j^2)}{4m^2\sigma^2}\right) I_0\left(\frac{ij}{2m^2\sigma^2}\right)\right] d\sigma$$

where m is number of rings on the sensor spiral, σ is the integration variable and $I_0(x)$ is a modified Bessel function. Thus, there are only two fit parameters in the equation, the thermal conductivity – k, and the thermal diffusivity – α.

The volumetric heat capacity ρc_p, where ρ is the density and c_p is the specific heat capacity is obtained from the ratio between the thermal conductivity and diffusivity:

$$\rho c_p = k/\alpha$$

5.3.2 Test procedure

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 ISO 22007-2:2015 (ISO 2015) for Determination of thermal conductivity and thermal diffusivity at RISE Fire and Safety. Emil Hallberg and Hasan Sokoti at RISE Fire and Safety conducted the thermal property measurements and prepared the pertinent sections of the report.

The thermal properties of the water-saturated specimens were measured in ambient air (23°C). In order to retain the water saturation and obtain the desired temperature, the specimens and the sensor were kept in a plastic bag during the measurements, see Figure 4-2.

Each pair of specimens was measured at least five times. The time lag between two repeated measurements was 50 minutes and every measurement was 40 s long. During the transient heating 200 data points of temperature increase are registered. Not all of them are used in the analysis as explained above. The result of each measurement was evaluated separately. The average value of all measurements for each specimen was calculated and presented here.

Measured raw data were saved and the analysis is saved for each measurement as Excel files. These files were stored on the hard disc of the measurement computer and sent to the project folder at the RISE network.

5.4 Indirect tensile strength test

The specimens had been stored more than 19 days in water when the indirect tensile strength was determined.

An auto-calibration of the load frame was run prior to the mechanical test in order to check the system. Further, an individual check-list was filled in and checked for every specimen during all the steps in the execution.

The diameter and thickness were entered into the test software which computed the indirect tensile strength together with the mean value and standard deviation for the whole test series. The results were then exported as text-files and stored in a file server on the RISE computer network.

A list of the activities conducted during the indirect tensile strength tests is shown in Table 5-3.

Table 5-3. Activities during the indirect tensile strength tests.

Step	Activity
1	The geometrical tolerances were checked: parallel and perpendicular surfaces, smooth and straight circumferential surface.
2	The diameter and thickness were measured three times each. The respective mean value determines the dimensions that are reported.
3	The direction of compressive loading was marked as a line on one of the plane surfaces with a marker pen.
4	The specimens were then put into water and stored in water for a minimum of 7 days. The weight of water together with one specimen was determined. The specimen was taken out from the water and the weight of the water and rock specimen was determined separately, and by using the known density of the water, the wet density could be computed. This procedure was repeated for each specimen.
5	A specimen was taken up from the water bath and the surface of the specimen where the strain gauge were going to be applied was dried using a cloth. The surface was then cleaned using acetone and ethanole, which in addition, further dries the surface. The strain gauge was then glued in the centre of the circular surface using a cyanoacrylate adhesive and fixated by a distributed force of 30-40 N against the gauge. The specimen was put back into water laying down with the planar surfaces in the horizontal direction and the strain gauge on the upper surface. The specimen was not fully submerged into water and the water level was just a bit under the upper surface in order not to wet the strain gauge. This step was repeated for a set of specimens with a number that could be tested during the same day as the gluing was done.
6	The specimens were inserted into the loading device one by one, with the correct orientation given by the marked line. The strain gauges were connected to the sampling device and the signals were checked. The specimens were loaded up to failure during deformation control. The displacement rate was set to 0.3 mm/min during loading. The maximum compressive load, which also defines the failure load, was registered.

5.5 Data handling

The test results were transferred to and stored in a file server on the RISE computer network after completed tests. Matlab, version R2020a, was used to produce the diagrams of the stress and strain measurements for the indirect tensile strength tests. MS Excel was used to produce the other diagrams and for reporting data to the SICADA database.

5.6 Nonconformities

The activity plan was followed with no departures.

6 Results

The reported parameters are based both on unprocessed raw data obtained from the testing and processed data and were reported to the Sicada database, where they are traceable by the activity plan number. These data together with the digital photographs of the individual specimens were handed over to SKB. The handling of the results follows SDP-508 (SKB internal controlling document) in general.

6.1 Density

The density of the specimens at a water-saturated condition is shown in the results tables for the mechanical tests in Section 6.3 and in Table 6-1. An overview of the results for all specimens is shown in Figure 6-1.

Table 6-1. Specimen dimensions and density of KFM24-90V-08 and KFM24-90V-09.

Identification	Diameter (mm)	Height (mm)	Density (kg/m^3)
KFM24-90V-08A	45.2	46.4	2687
KFM24-90V-08B	45.2	42.3	2694
KFM24-90V-09C	45.2	42.3	2692
KFM24-90V-09D	45.2	42.3	2693

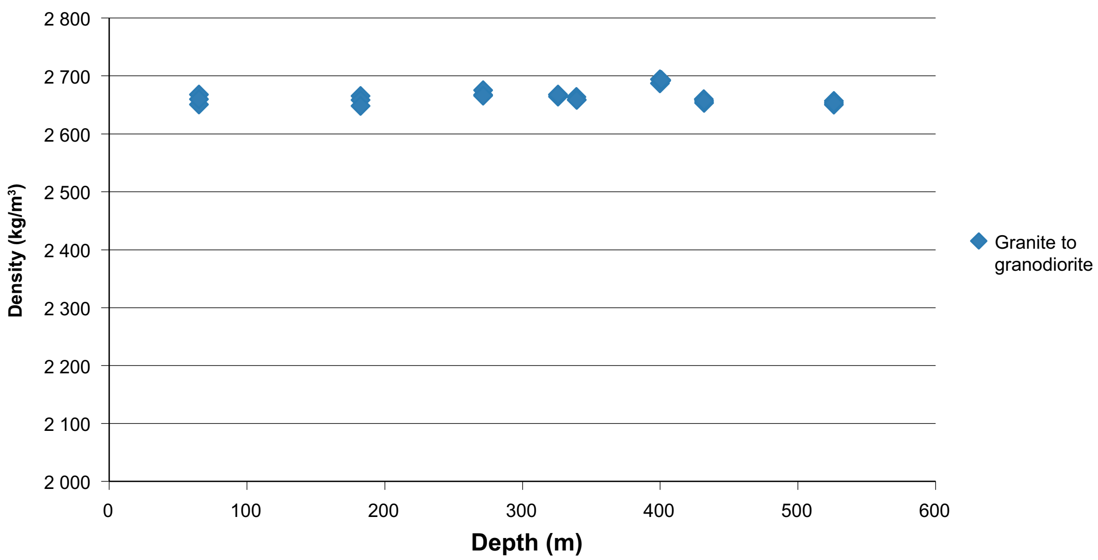


Figure 6-1. *Density as a function of borehole depth.*

6.2 Thermal properties

6.2.1 Pictures of the specimens

Photos taken of the specimens are found in the results section of the indirect tensile strength tests, section 6.3.1, and in Figures 6-2 and 6-3 below.

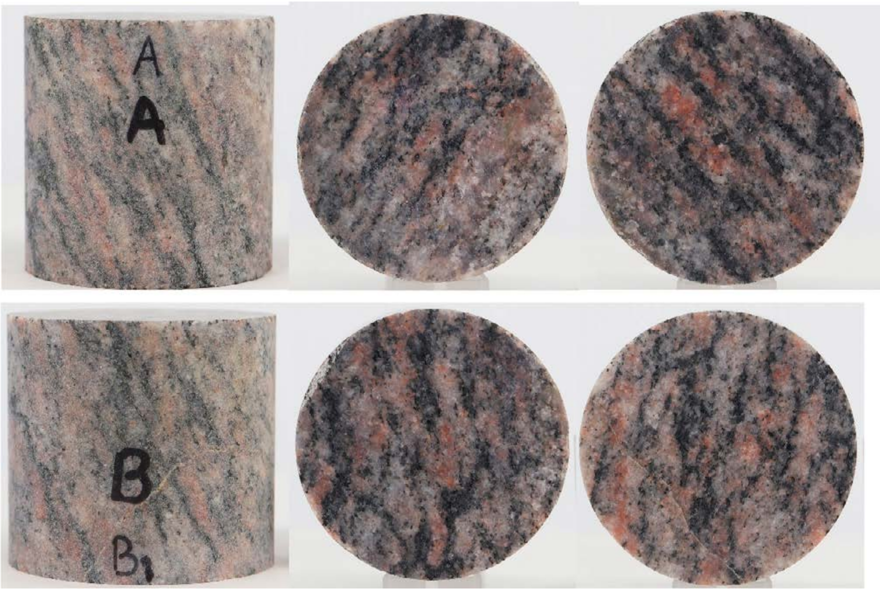


Figure 6-2. *Specimen KFM24-90V-08 that consists of par A and B. Side, front and back view.*

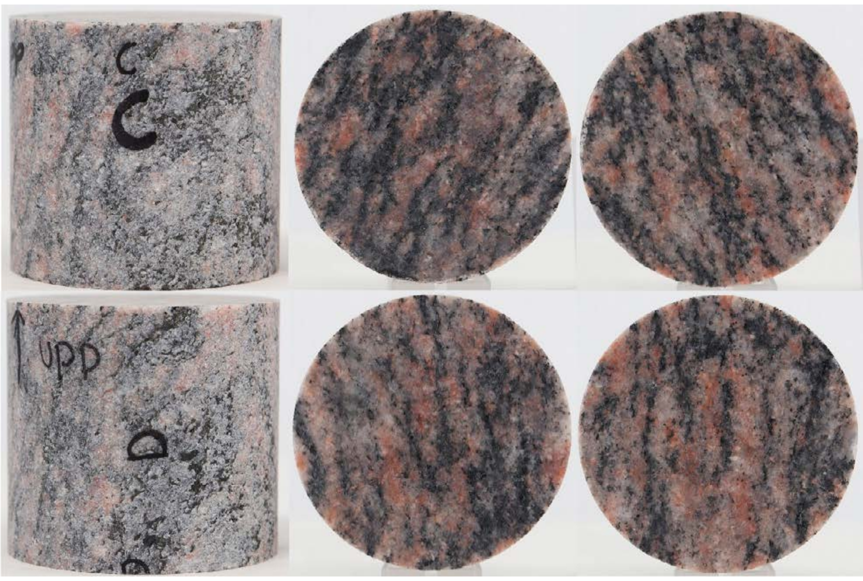


Figure 6-3. *Specimen KFM24-90V-09 that consists of part C and D. Side, front and back view.*

6.2.2 Results for each individual specimen

The average results of at least 4 individual measurements for each interface measured are presented in Table 6-2 along with the standard deviations between individual measurements in Table 6-3. The standard deviations are less than 1.0 % for conductivity (median 0.7 %), 5.7 % for diffusivity (median 1.9 %) and 4.9 % for volumetric specific heat (median 2.4 %).

Table 6-2. Mean value of thermal properties of samples at 23 °C. All measurements were 40 s long.

Identification	Heating power [mW]	Points analyzed	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Volumetric heat capacity [MJ/(m^3, K)]	No. of measurements*
KFM24-90V-01	350	50–95	3.626	1.77	2.05	7
KFM24-90V-02	350	45–95	3.125	2.03	2.03	5
KFM24-90V-03	350	40–105	3.368	1.84	1.84	5
KFM24-90V-04	350	50–95	3.536	2.00	1.77	4
KFM24-90V-05	350	50–110	3.544	1.76	2.01	5
KFM24-90V-06	350	50–100	3.292	1.77	1.86	6
KFM24-90V-07	350	50–100	3.304	1.88	1.76	5
KFM24-90V-08	350	25–116	3.500	1.76	1.99	9
KFM24-90V-09	350	65–110	3.763	1.66	2.27	10

* Number used in the calculation of the average parameters.

Table 6-3. Standard deviation of measured values at 23°C.

Identification	Conductivity [W/(m, K)]	Diffusivity [mm^2/s]	Vomumetric heat capacity [MJ/(m^3, K)]
KFM24-90V-01	0.011	0.028	0.036
KFM24-90V-02	0.019	0.071	0.067
KFM24-90V-03	0.017	0.051	0.060
KFM24-90V-04	0.033	0.091	0.092
KFM24-90V-05	0.005	0.009	0.009
KFM24-90V-06	0.019	0.033	0.044
KFM24-90V-07	0.026	0.028	0.040
KFM24-90V-08	0.024	0.011	0.013
KFM24-90V-09	0.039	0.030	0.046

6.2.3 Results for the entire test series

The thermal conductivity and thermal diffusivity of specimens representing different depths at 23°C were in the range 3.1–3.8 W/(m, K) and 1.8–2.0 mm^2/s. From these results the volumetric heat capacity was calculated to range between 1.8 and 2.3 MJ/(m^3, K). Graphical representation of the thermal conductivity and volumetric heat capacity versus borehole depth are given in Figure 6-4 and 6-5, respectively. The results of specimen KFM24-90V-01 (depth c. 65 m) show slightly higher values and specimen KFM24-90V-02 (depth c. 182 m) show slightly lower values of both the thermal conductivity and volumetric heat capacity, although the differences are small.

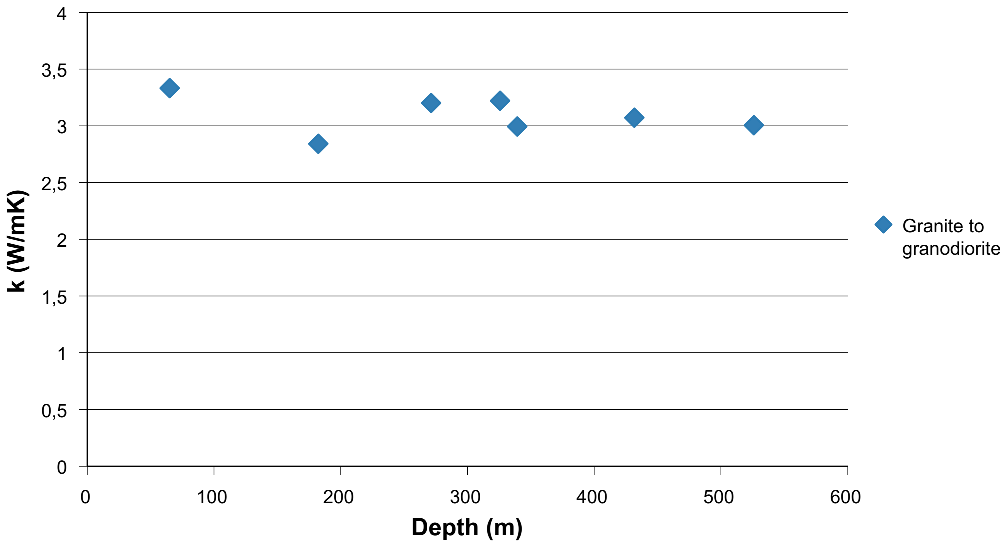


***Figure 6-4.** Thermal conductivity as a function of depth (not length in the inclined borehole).*

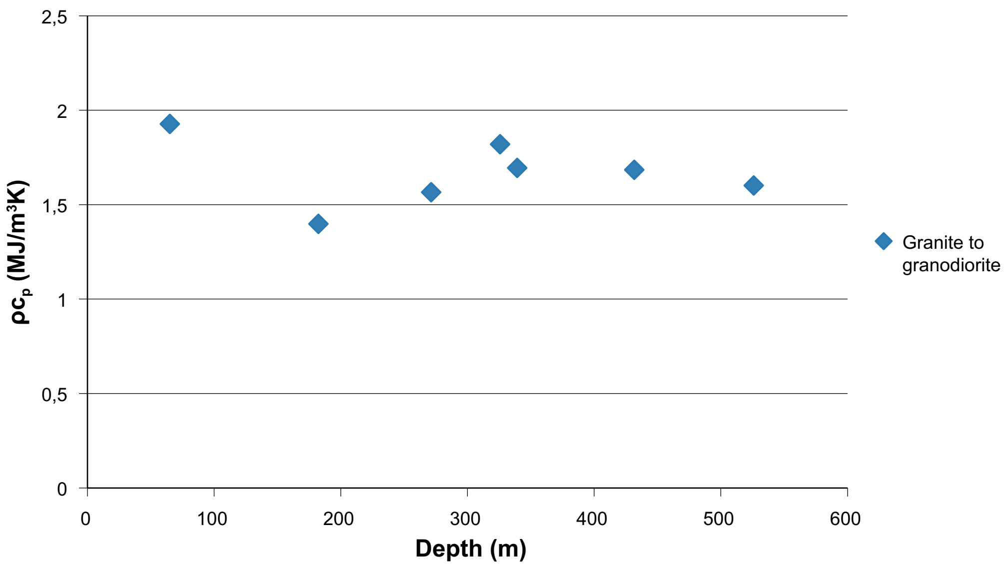


***Figure 6-5.** Volumetric heat capacity as a function of depth.*

6.3 Indirect tensile strength test

6.3.1 Results for each individual specimen

The results and photographs for the individual specimens are presented below.

Specimen ID: KFM24-110-01

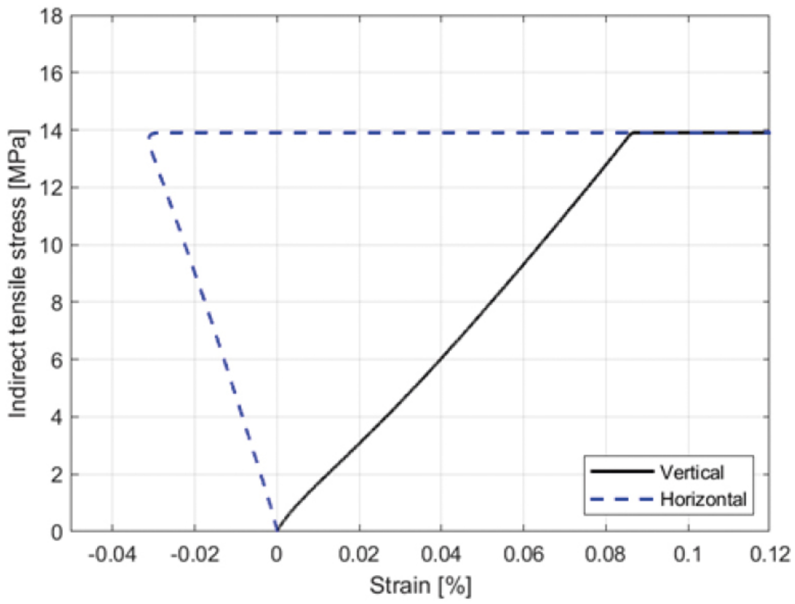
Before mechanical test

After mechanical test

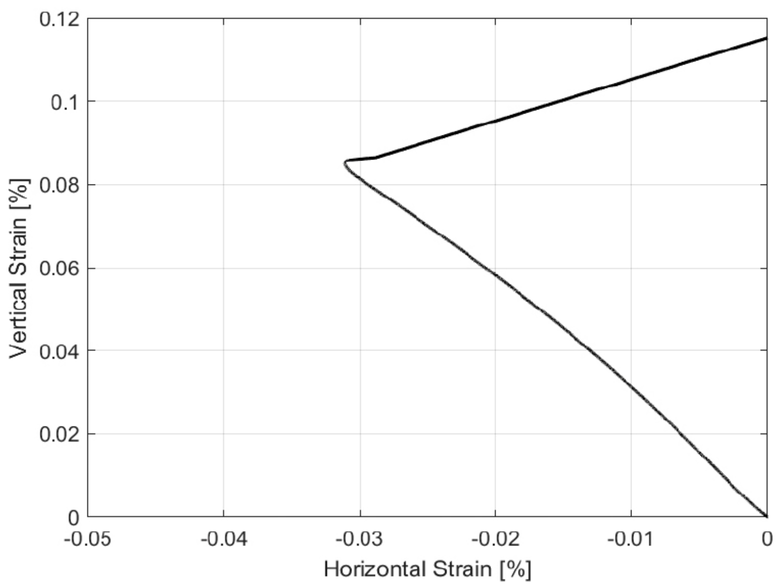
Diameter (mm)	Height (mm)	Density (kg/m^3)	Tensile strength (MPa)
45.0	27.4	2668	13.9

Comments: None

Specimen ID: KFM24-110-01

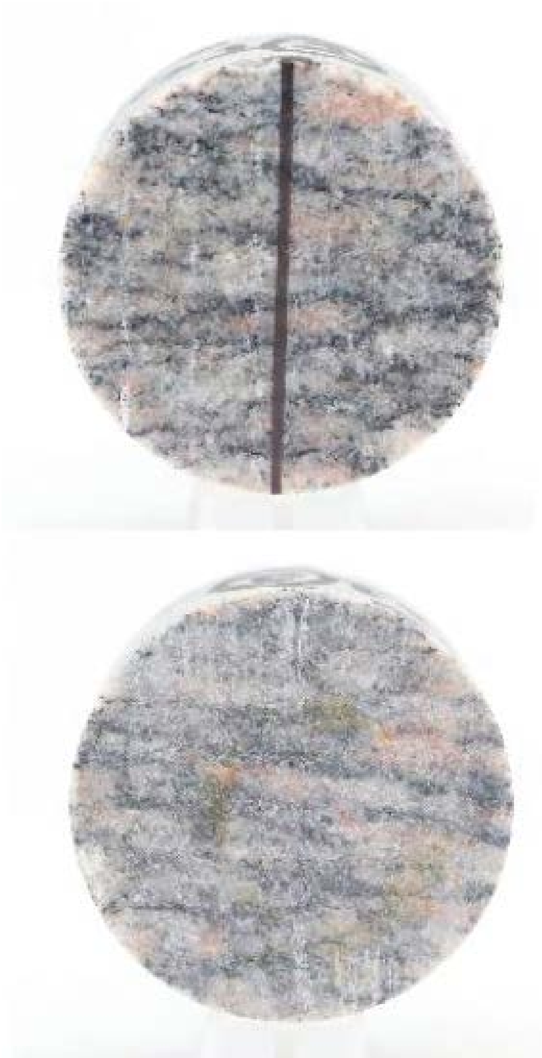


Specimen ID: KFM24-110-01



Specimen ID: KFM24-110-02

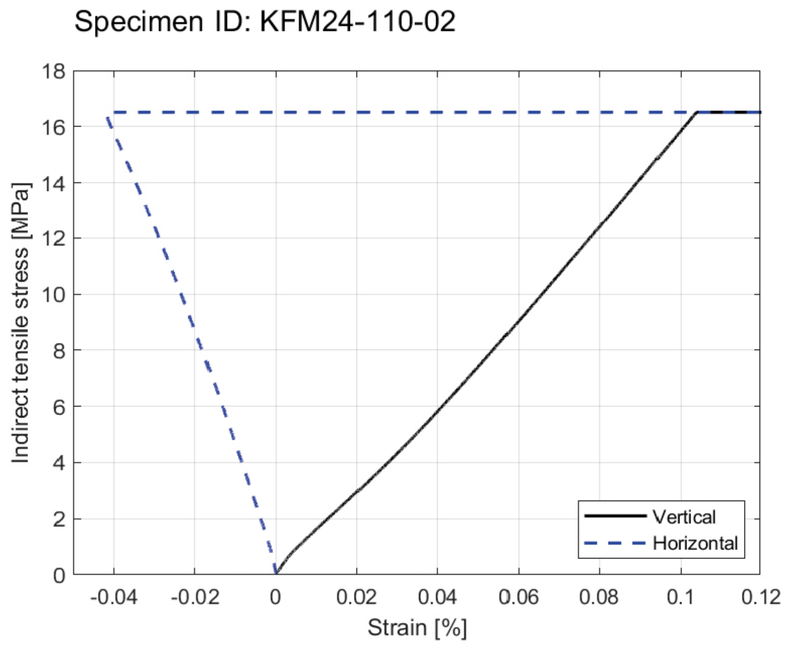
Before mechanical test



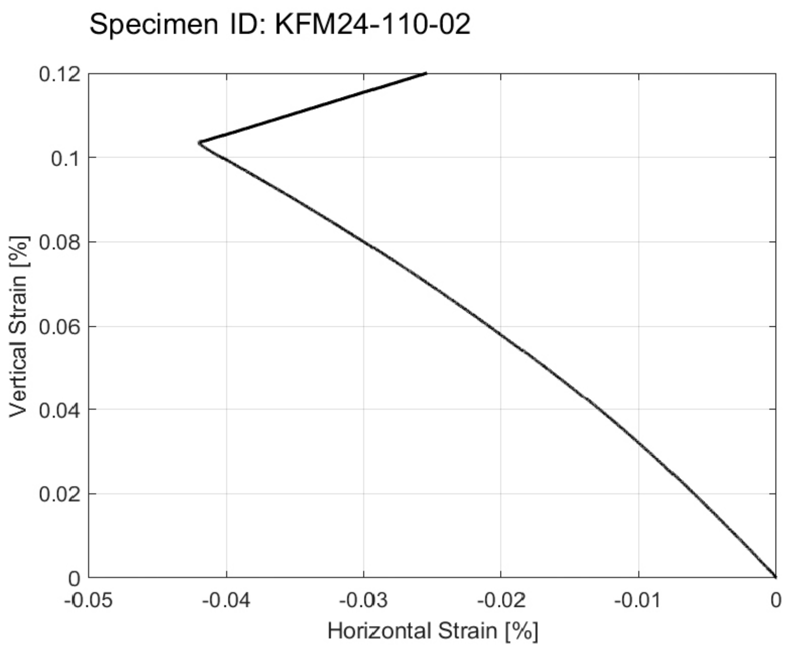
After mechanical test

Diameter (mm)	Height (mm)	Density (kg/m^3)	Tensile strength (MPa)
45.0	27.2	2650	16.5

Comments: None



Specimen ID: KFM24-110-02
Indirect tensile stress [MPa]
Strain [%]
Vertical
Horizontal
18
16
14
12
10
8
6
4
2
0
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12



Specimen ID: KFM24-110-02
Vertical Strain [%]
Horizontal Strain [%]
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.05
-0.04
-0.03
-0.02
-0.01
0

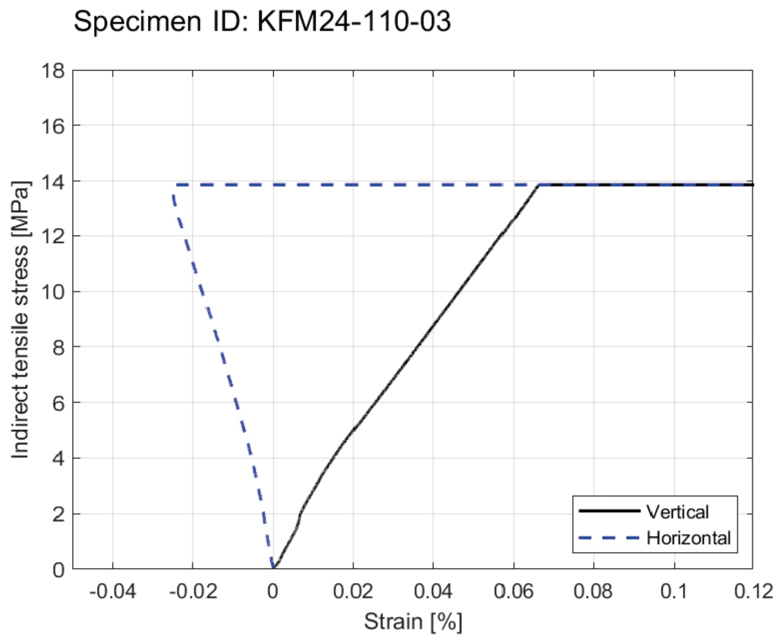
Specimen ID: KFM24-110-03

Before mechanical test

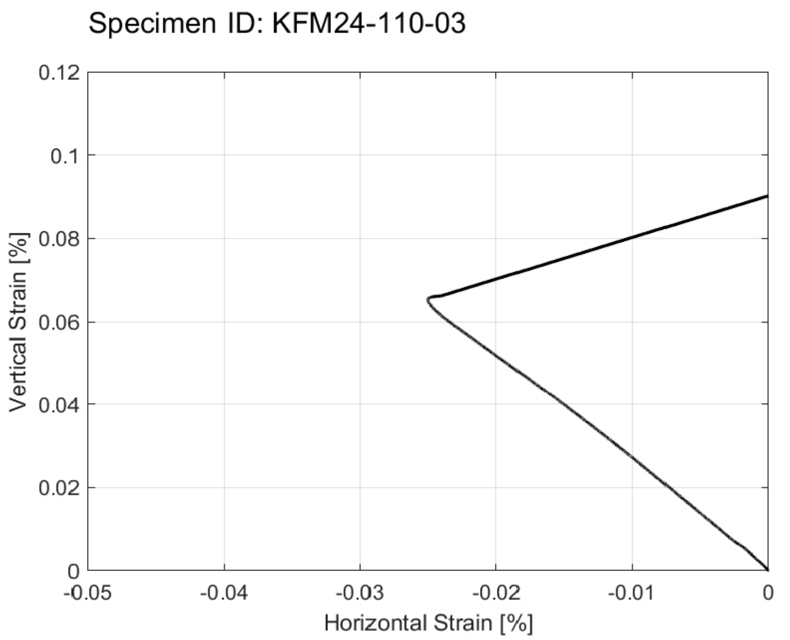
After mechanical test

Diameter (mm)	Height (mm)	Density (kg/m^3)	Tensile strength (MPa)
45.0	28.1	2660	13.9

Comments: None



Specimen ID: KFM24-110-03
Indirect tensile stress [MPa]
Strain [%]
Vertical
Horizontal



Specimen ID: KFM24-110-03
Vertical Strain [%]
Horizontal Strain [%]

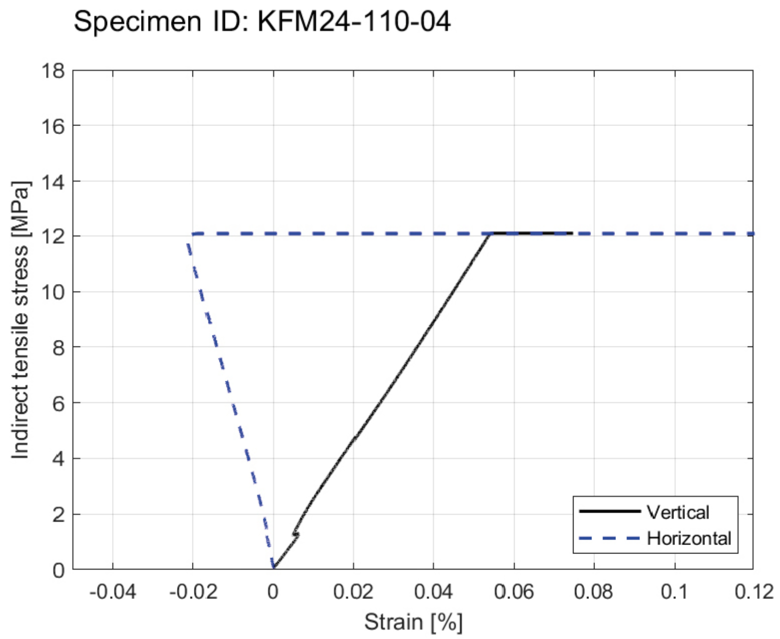
Specimen ID: KFM24-110-04

Before mechanical test

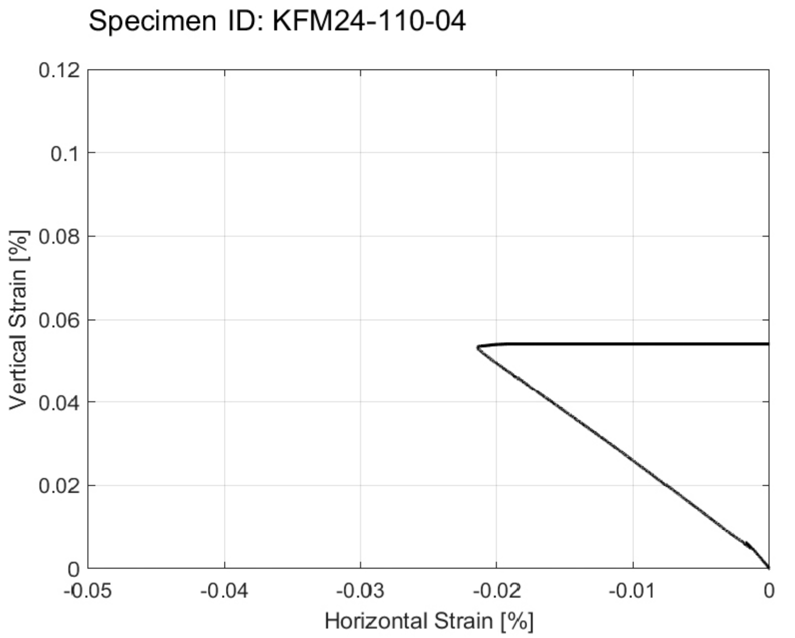
After mechanical test

Diameter (mm)	Height (mm)	Density (kg/m^3)	Tensile strength (MPa)
45.1	27.5	2665	12.1

Comments: None



Specimen ID: KFM24-110-04
Indirect tensile stress [MPa]
18
16
14
12
10
8
6
4
2
0
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12
Strain [%]
Vertical
Horizontal



Specimen ID: KFM24-110-04
Vertical Strain [%]
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.05
-0.04
-0.03
-0.02
-0.01
0
Horizontal Strain [%]

Specimen ID: KFM24-110-05

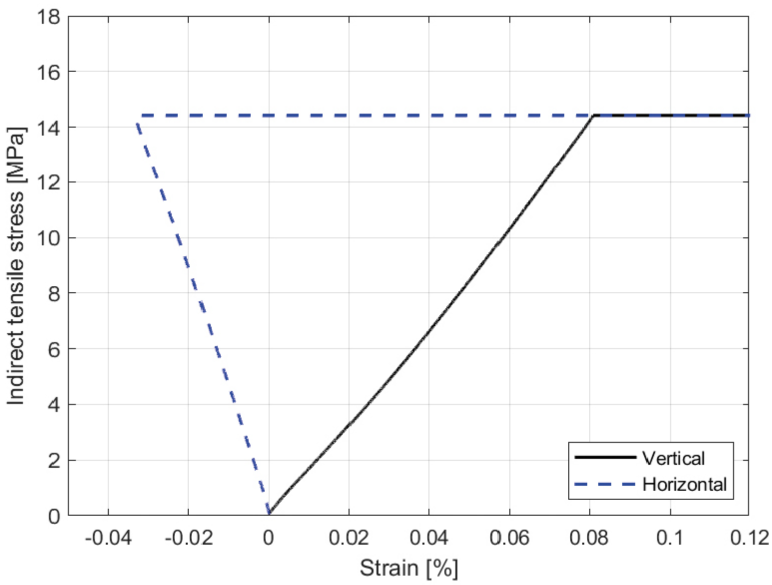
Before mechanical test

After mechanical test

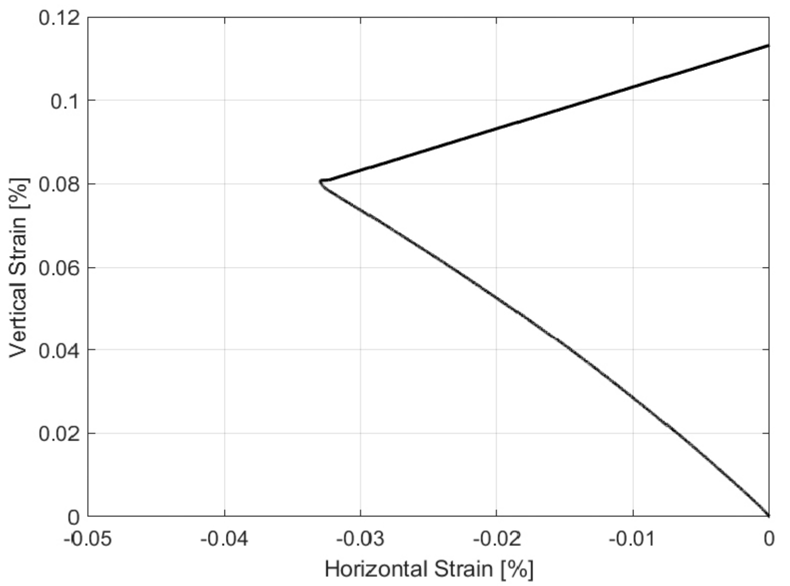
Diameter (mm)	**Height (mm)**	**Density (kg/m^3)**	**Tensile strength (MPa)**
45.1	27.8	2658	14.4

Comments: None

Specimen ID: KFM24-110-05



Specimen ID: KFM24-110-05



Specimen ID: KFM24-110-06

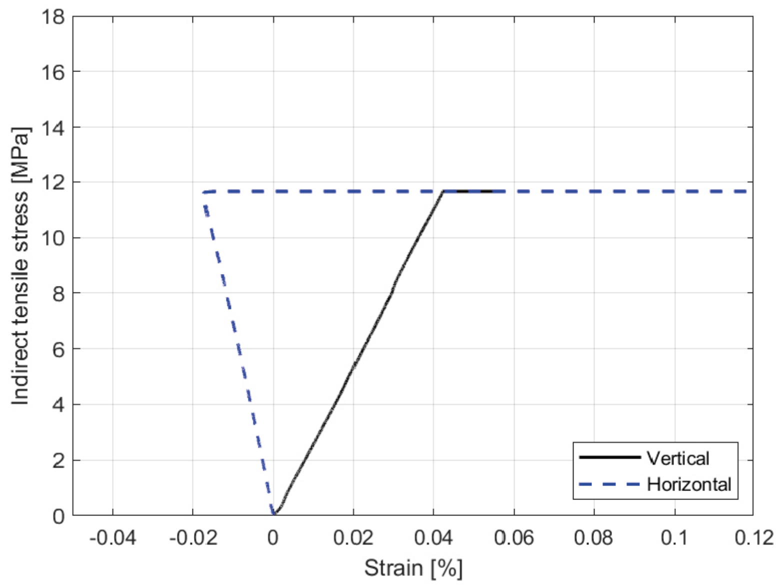
Before mechanical test

After mechanical test

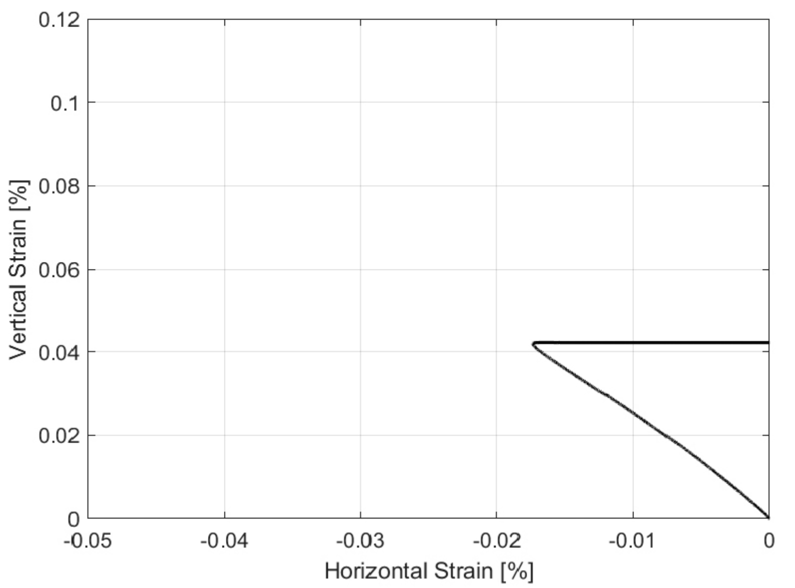
Diameter (mm)	**Height (mm)**	**Density (kg/m³)**	**Tensile strength (MPa)**
45.1	28.1	2648	11.7

Comments: None

Specimen ID: KFM24-110-06



Specimen ID: KFM24-110-06



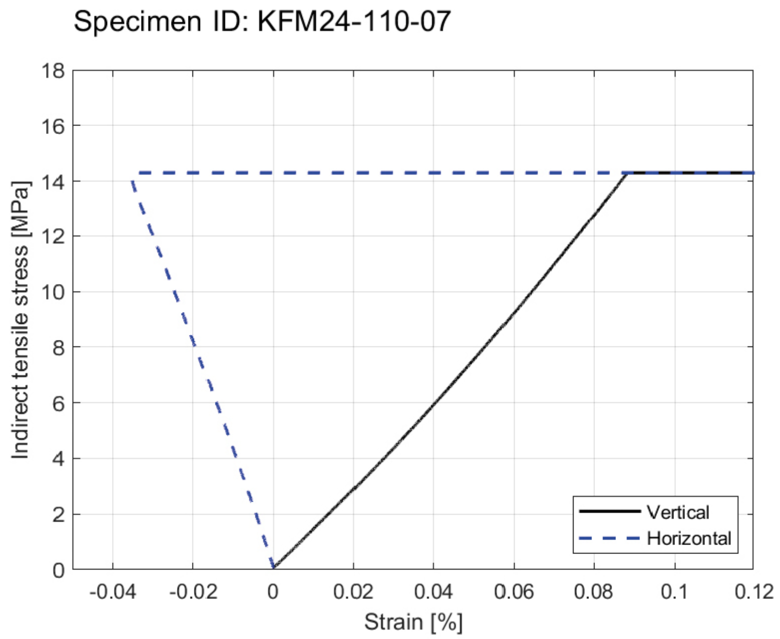
Specimen ID: KFM24-110-07

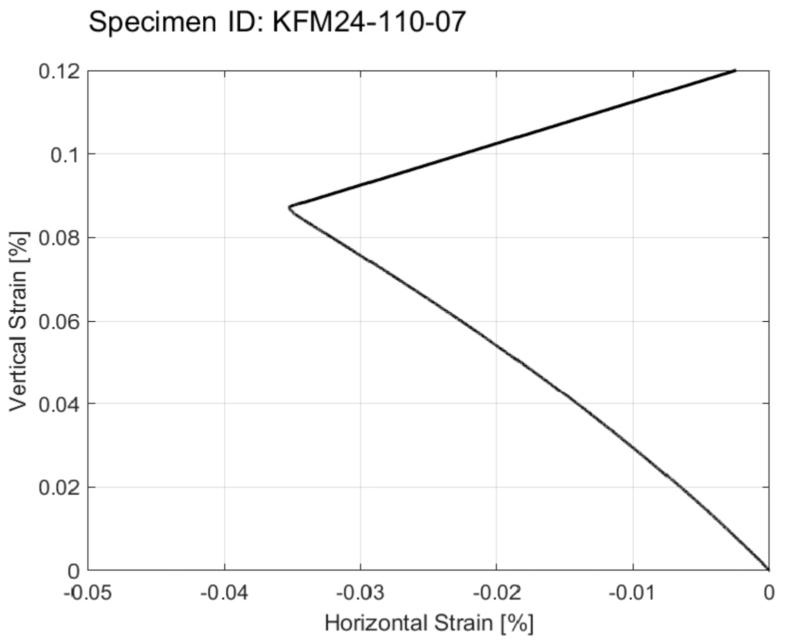
Before mechanical test

After mechanical test

Diameter (mm)	**Height (mm)**	**Density (kg/m^3)**	**Tensile strength (MPa)**
45.2	27.5	2667	14.3

Comments: None


Specimen ID: KFM24-110-07
Indirect tensile stress [MPa]
Strain [%]
Vertical
Horizontal
18
16
14
12
10
8
6
4
2
0
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12


Specimen ID: KFM24-110-07
Vertical Strain [%]
Horizontal Strain [%]
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.05
-0.04
-0.03
-0.02
-0.01
0

Specimen ID: KFM24-110-08

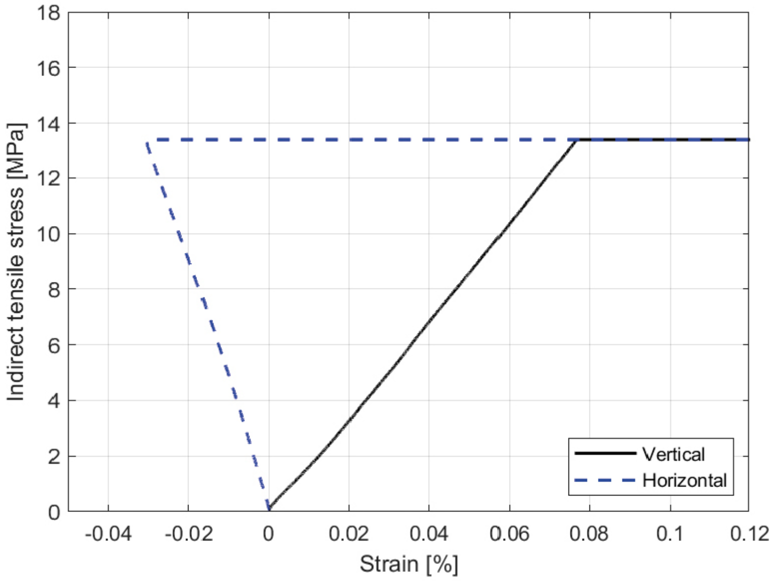
Before mechanical test

After mechanical test

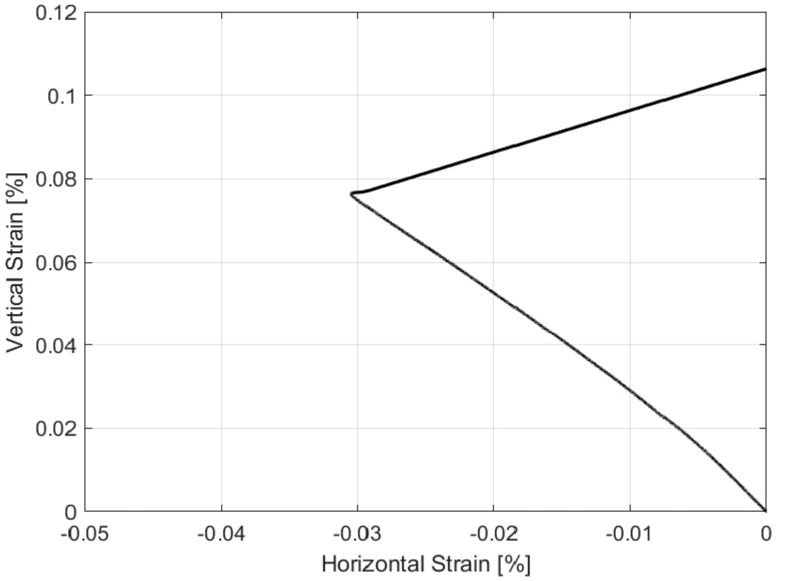
Diameter (mm)	**Height (mm)**	**Density (kg/m³)**	**Tensile strength (MPa)**
45.2	27.8	2675	13.4

Comments: None

Specimen ID: KFM24-110-08



Specimen ID: KFM24-110-08



Specimen ID: KFM24-110-09

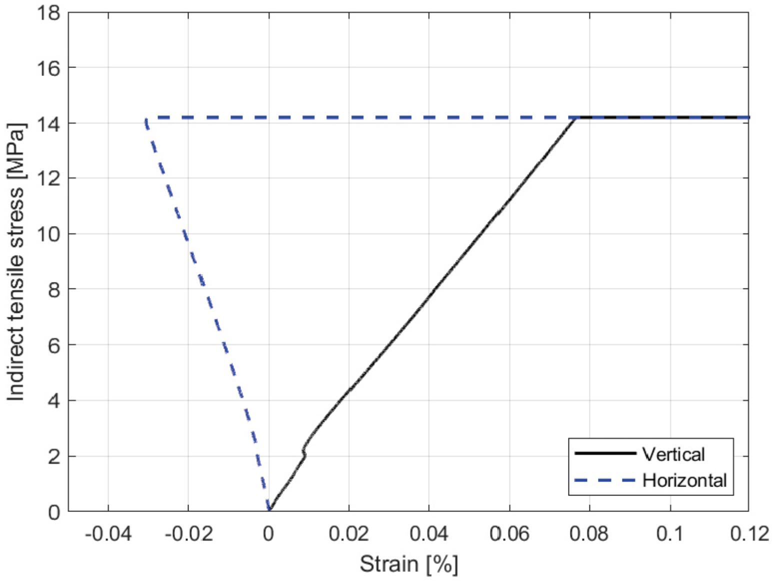
Before mechanical test

After mechanical test

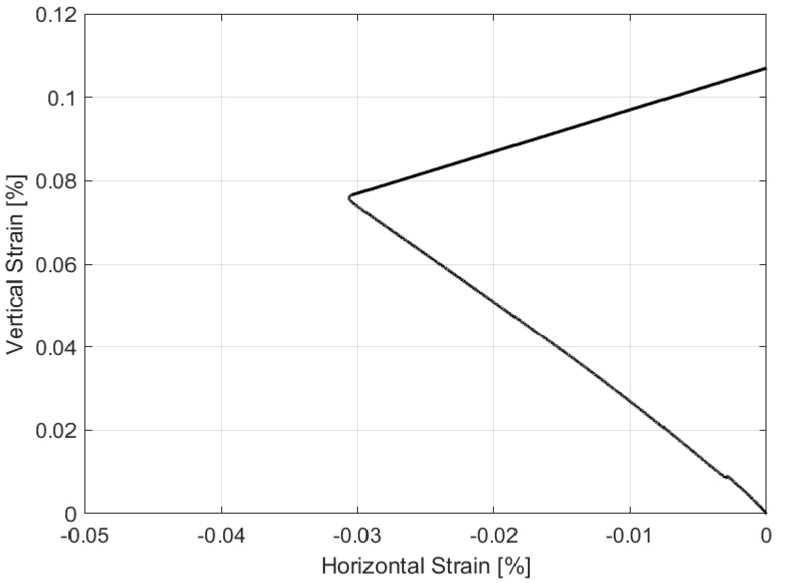
Diameter (mm)	Height (mm)	Density (kg/m^3)	Tensile strength (MPa)
45.2	28.0	2665	14.2

Comments: None

Specimen ID: KFM24-110-09



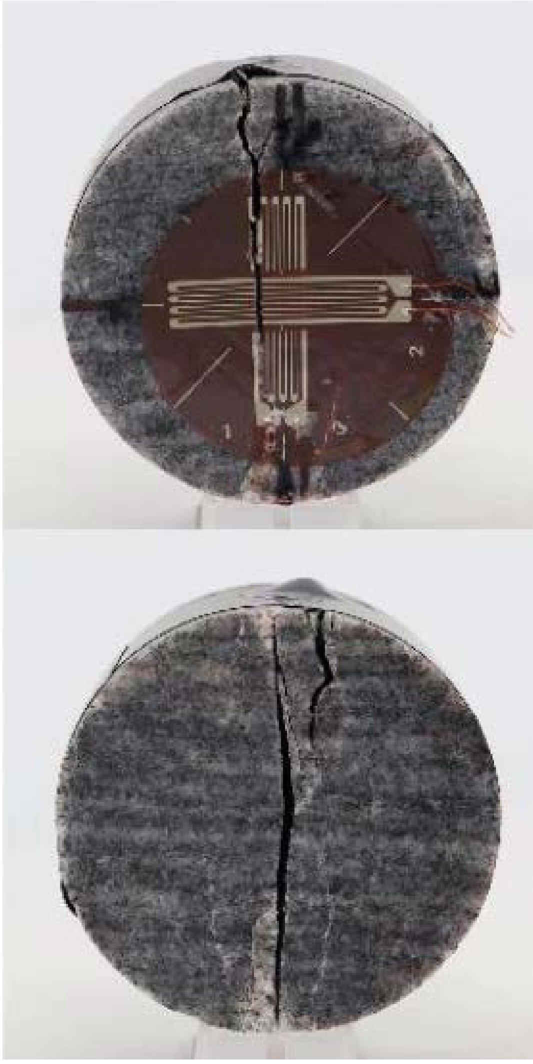
Specimen ID: KFM24-110-09



Specimen ID: KFM24-110-10

Before mechanical test

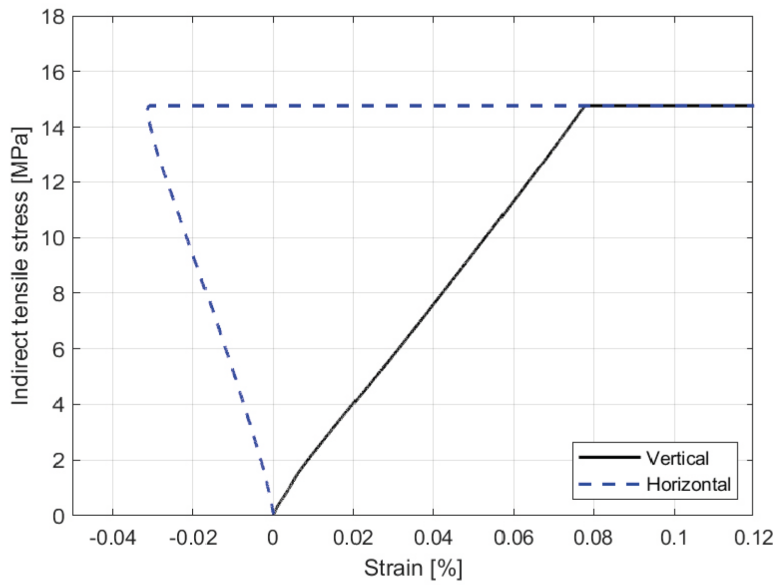
After mechanical test



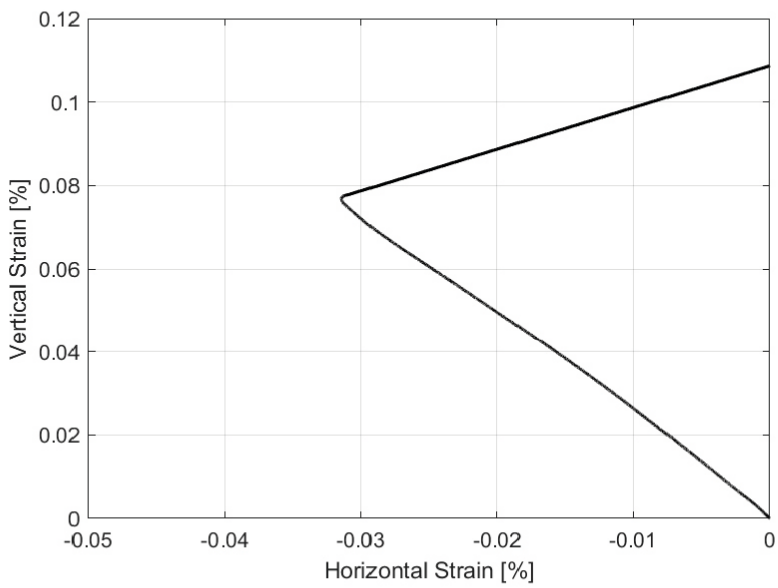
Diameter (mm)	**Height (mm)**	**Density (kg/m^3)**	**Tensile strength (MPa)**
45.1	27.8	2 668	14.8

Comments: None

Specimen ID: KFM24-110-10



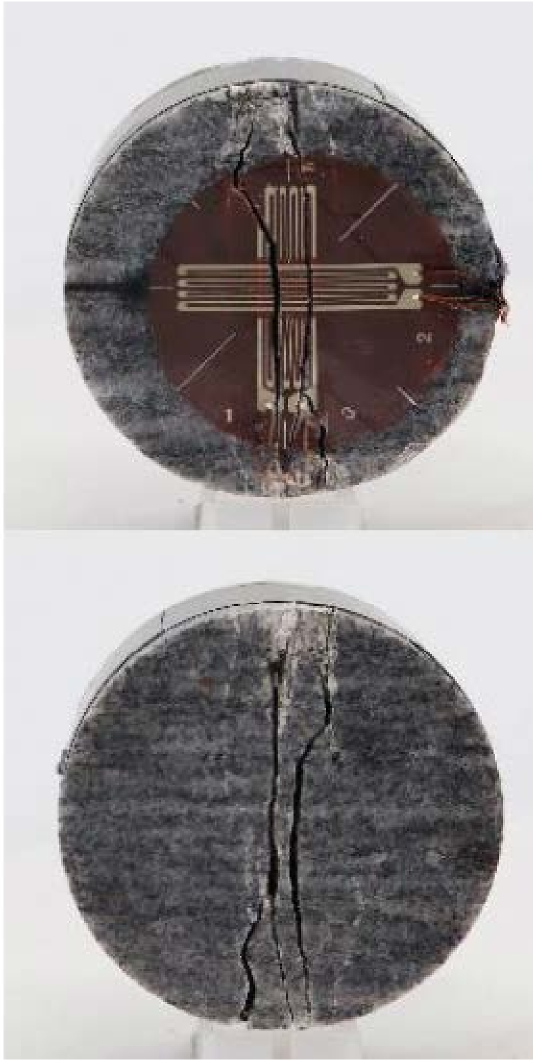
Specimen ID: KFM24-110-10



Specimen ID: KFM24-110-11

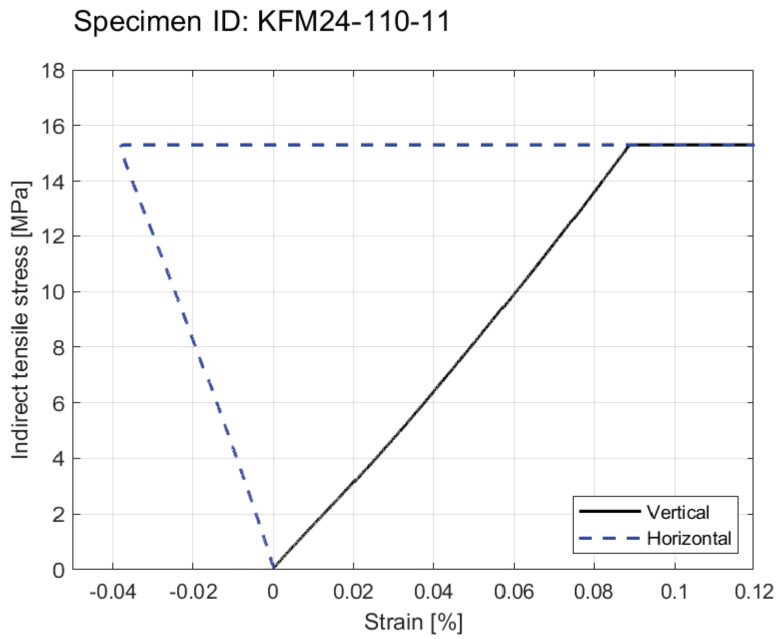
Before mechanical test

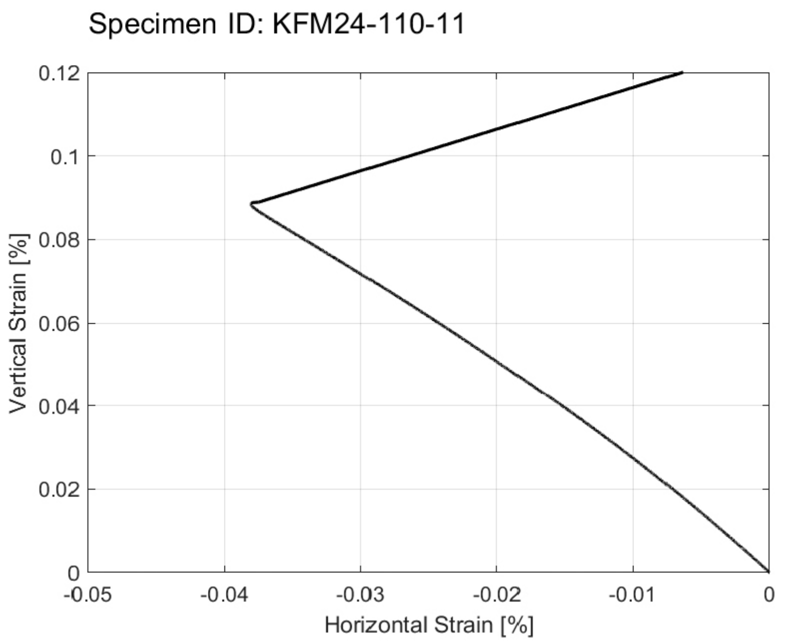
After mechanical test



Diameter (mm)	**Height (mm)**	**Density (kg/m^3)**	**Tensile strength (MPa)**
45.1	27.8	2664	15.3

Comments: None


Specimen ID: KFM24-110-11
Indirect tensile stress [MPa]
18
16
14
12
10
8
6
4
2
0
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12
Strain [%]
Vertical
Horizontal


Specimen ID: KFM24-110-11
Vertical Strain [%]
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.05
-0.04
-0.03
-0.02
-0.01
0
Horizontal Strain [%]

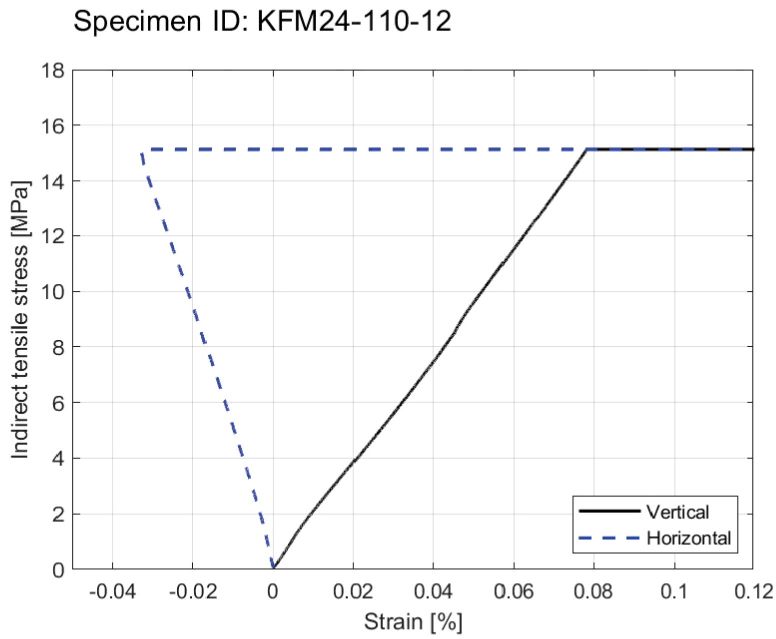
Specimen ID: KFM24-110-12

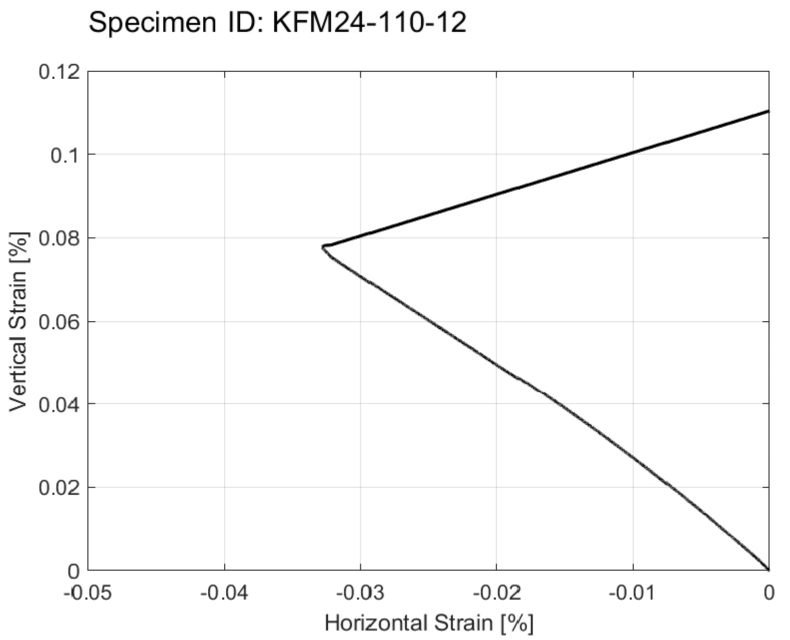
Before mechanical test

After mechanical test

Diameter (mm)	Height (mm)	Density (kg/m^3)	Tensile strength (MPa)
45.1	28.2	2667	15.1

Comments: None


Specimen ID: KFM24-110-12
Indirect tensile stress [MPa]
Strain [%]
Vertical
Horizontal
18
16
14
12
10
8
6
4
2
0
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12


Specimen ID: KFM24-110-12
Vertical Strain [%]
Horizontal Strain [%]
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.05
-0.04
-0.03
-0.02
-0.01
0

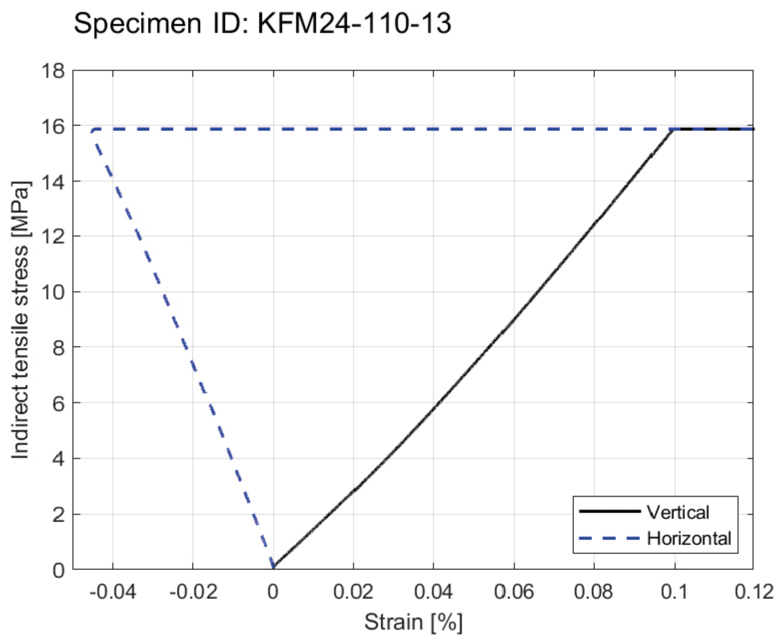
Specimen ID: KFM24-110-13

Before mechanical test

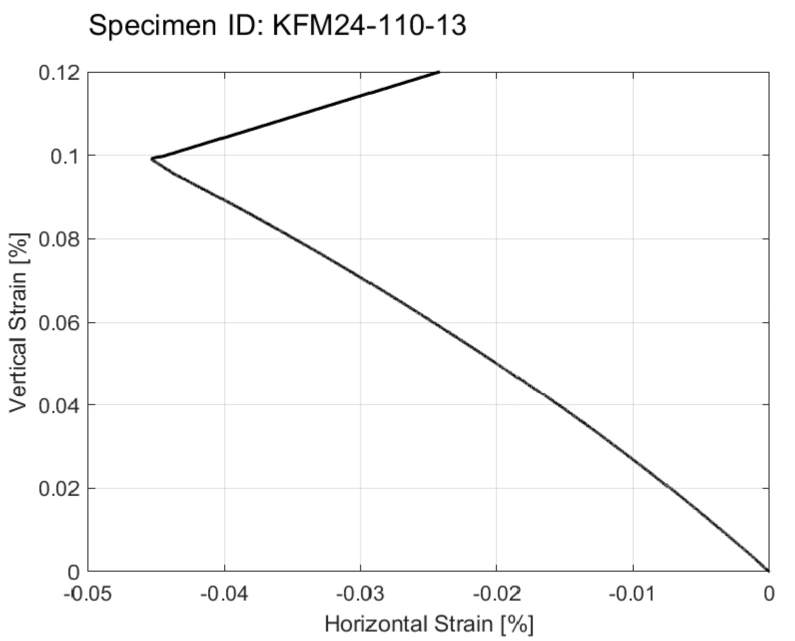
After mechanical test

Diameter (mm)	Height (mm)	Density (kg/m^3)	Tensile strength (MPa)
45.1	27.9	2663	15.9

Comments: None



Specimen ID: KFM24-110-13
Indirect tensile stress [MPa]
Strain [%]
Vertical
Horizontal
18
16
14
12
10
8
6
4
2
0
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12



Specimen ID: KFM24-110-13
Vertical Strain [%]
Horizontal Strain [%]
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.05
-0.04
-0.03
-0.02
-0.01
0

Specimen ID: KFM24-110-14

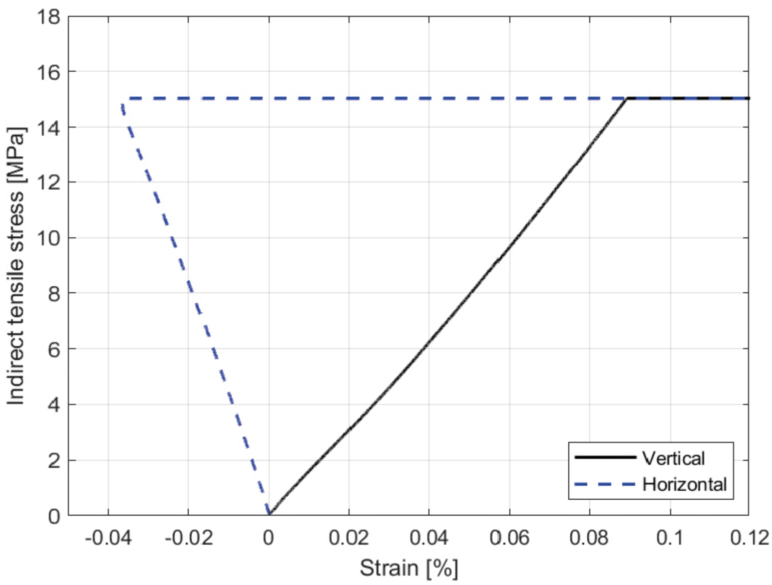
Before mechanical test

After mechanical test

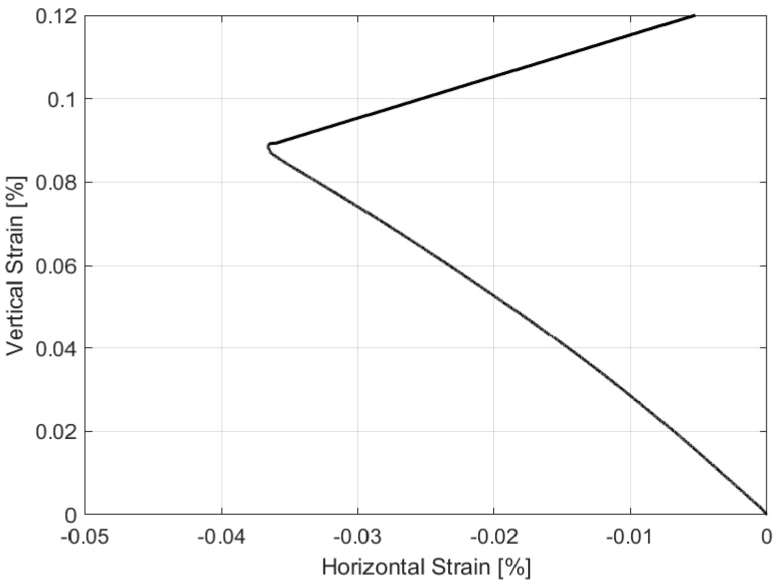
Diameter (mm)	Height (mm)	Density (kg/m^3)	Tensile strength (MPa)
45.1	28.0	2659	15.0

Comments: None

Specimen ID: KFM24-110-14



Specimen ID: KFM24-110-14



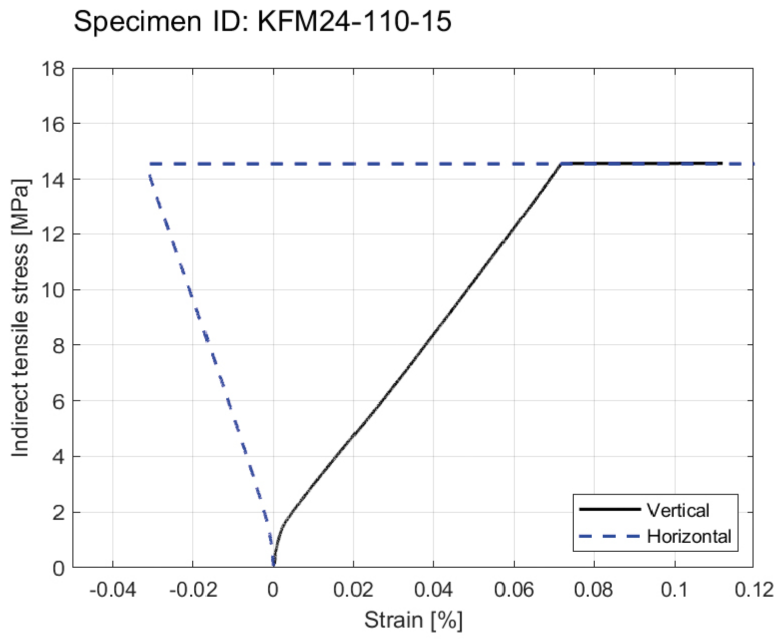
Specimen ID: KFM24-110-15

Before mechanical test

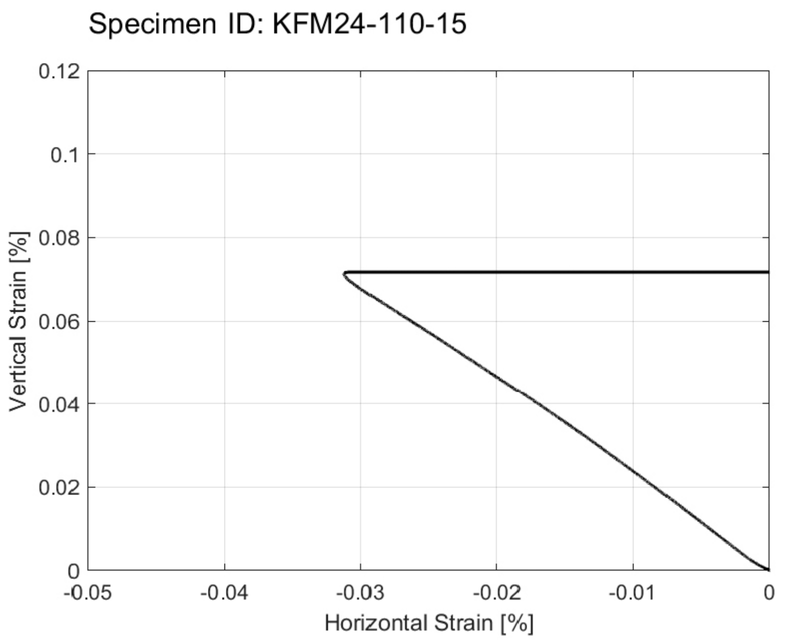
After mechanical test

Diameter (mm)	**Height (mm)**	**Density (kg/m³)**	**Tensile strength (MPa)**
45.1	28.1	2659	14.6

Comments: None



Specimen ID: KFM24-110-15
Indirect tensile stress [MPa]
Strain [%]
Vertical
Horizontal
18
16
14
12
10
8
6
4
2
0
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12



Specimen ID: KFM24-110-15
Vertical Strain [%]
Horizontal Strain [%]
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.05
-0.04
-0.03
-0.02
-0.01
0

Specimen ID: KFM24-110-16

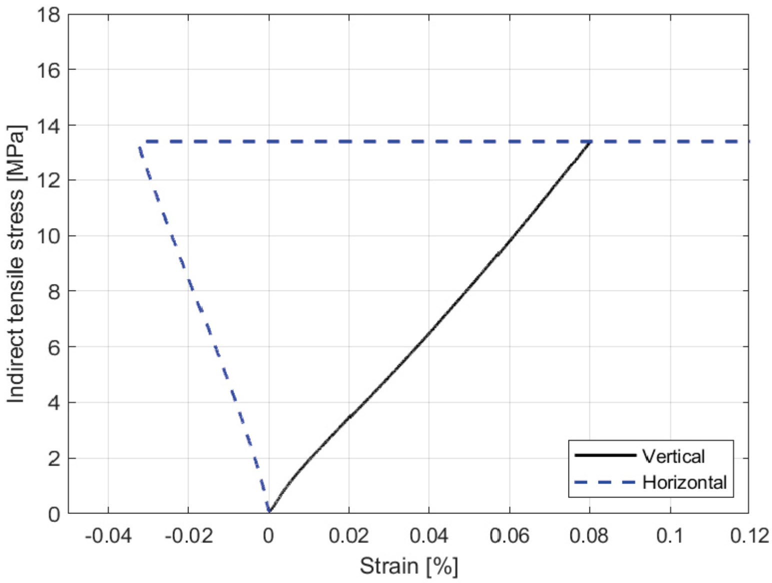
Before mechanical test

After mechanical test

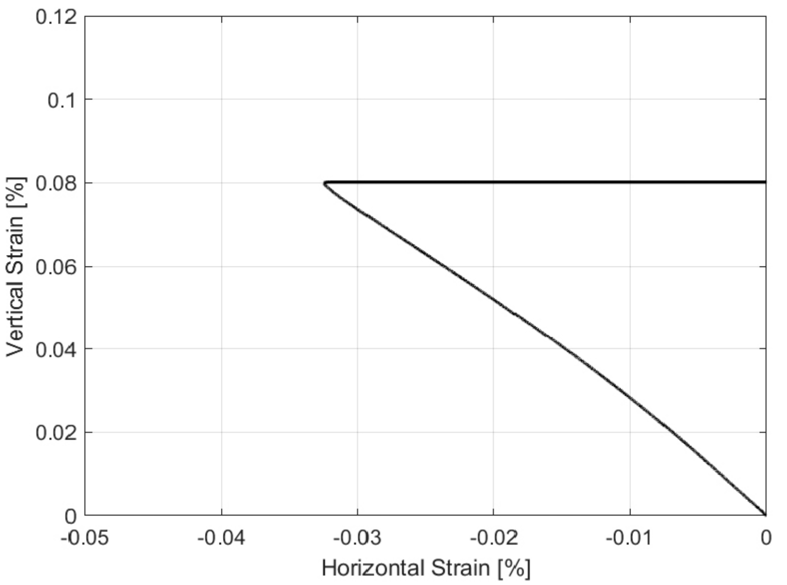
Diameter (mm)	**Height (mm)**	**Density (kg/m^3)**	**Tensile strength (MPa)**
45.1	26.4	2660	13.4

Comments: None

Specimen ID: KFM24-110-16



Specimen ID: KFM24-110-16



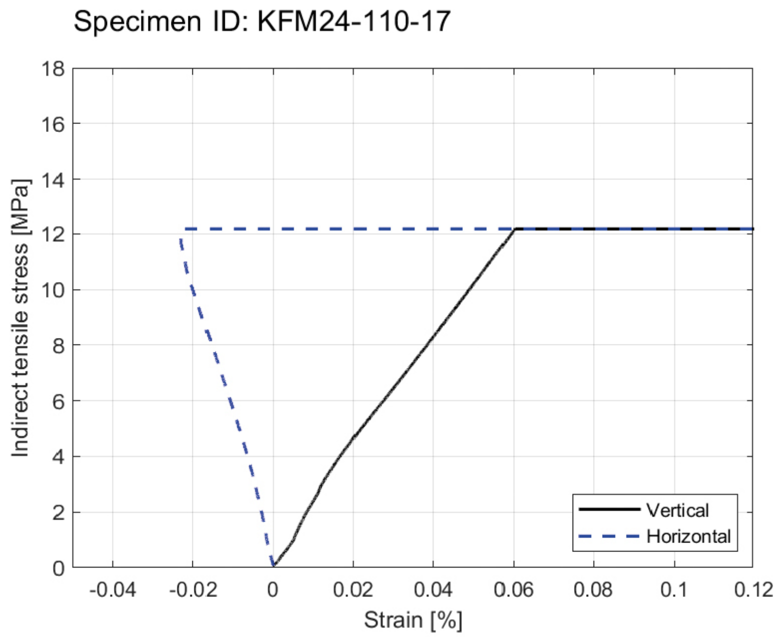
Specimen ID: KFM24-110-17

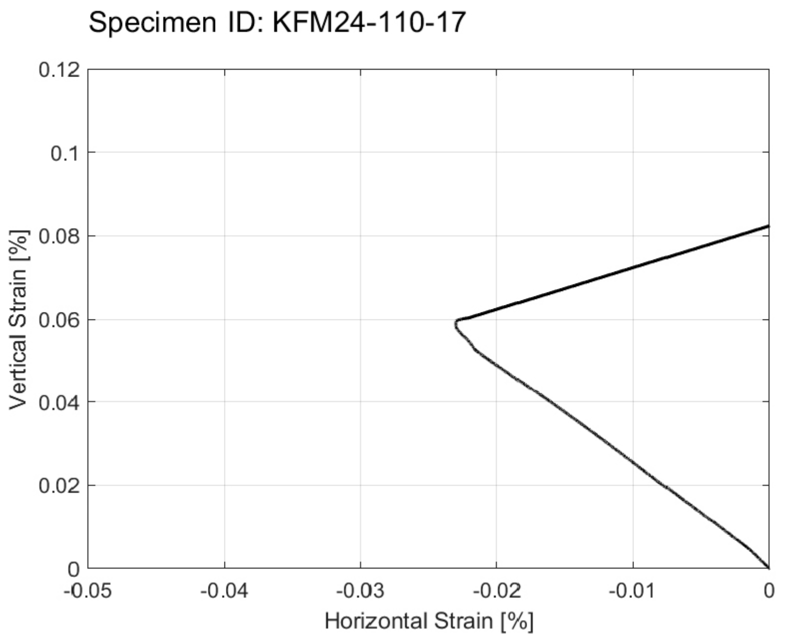
Before mechanical test

After mechanical test

Diameter (mm)	Height (mm)	Density (kg/m^3)	Tensile strength (MPa)
45.1	27.9	2653	12.2

Comments: None


Specimen ID: KFM24-110-17
Indirect tensile stress [MPa]
Strain [%]
Vertical
Horizontal
18
16
14
12
10
8
6
4
2
0
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12


Specimen ID: KFM24-110-17
Vertical Strain [%]
Horizontal Strain [%]
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.05
-0.04
-0.03
-0.02
-0.01
0

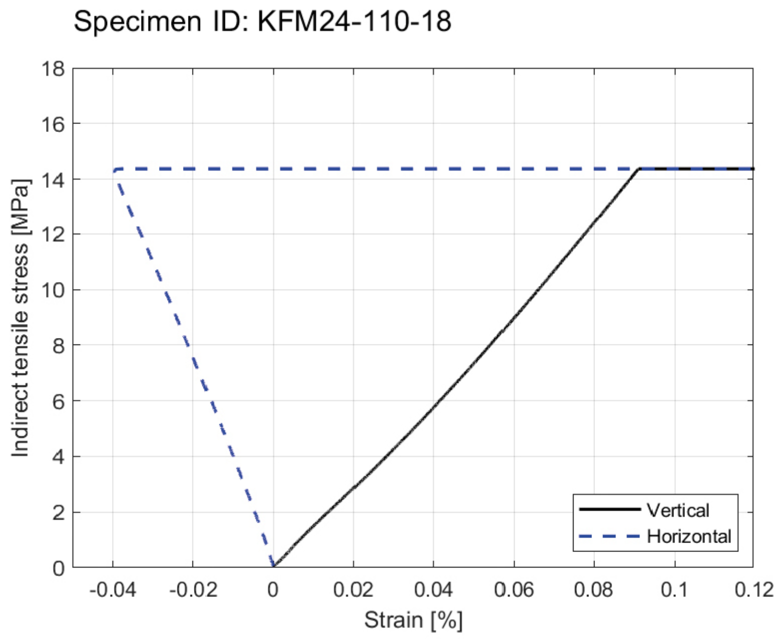
Specimen ID: KFM24-110-18

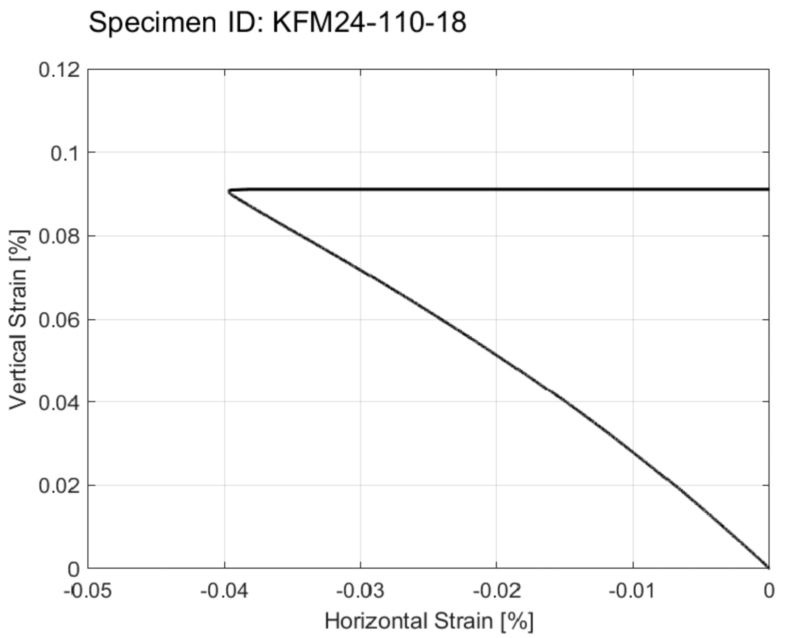
Before mechanical test

After mechanical test

Diameter (mm)	**Height (mm)**	**Density (kg/m^3)**	**Tensile strength (MPa)**
45.1	27.9	2657	14.4

Comments: None


Specimen ID: KFM24-110-18
Indirect tensile stress [MPa]
Strain [%]
Vertical
Horizontal
18
16
14
12
10
8
6
4
2
0
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12


Specimen ID: KFM24-110-18
Vertical Strain [%]
Horizontal Strain [%]
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.05
-0.04
-0.03
-0.02
-0.01
0

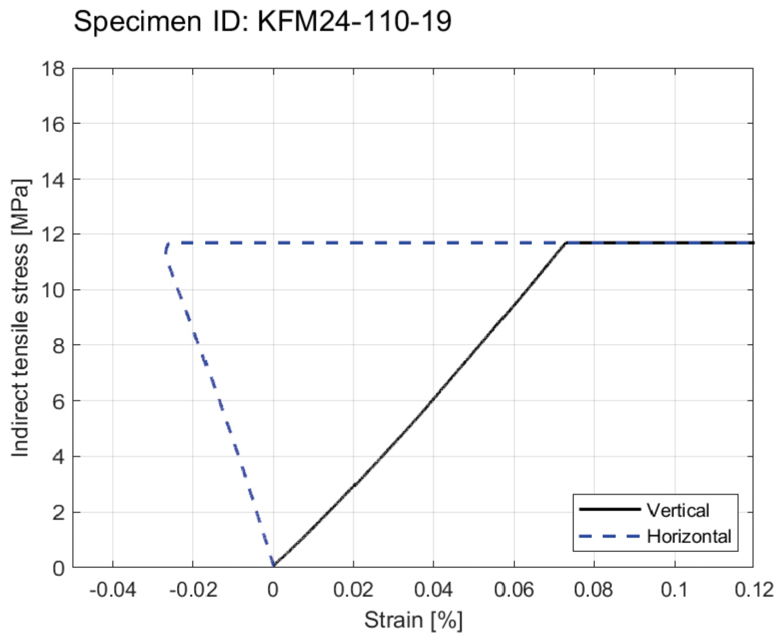
Specimen ID: KFM24-110-19

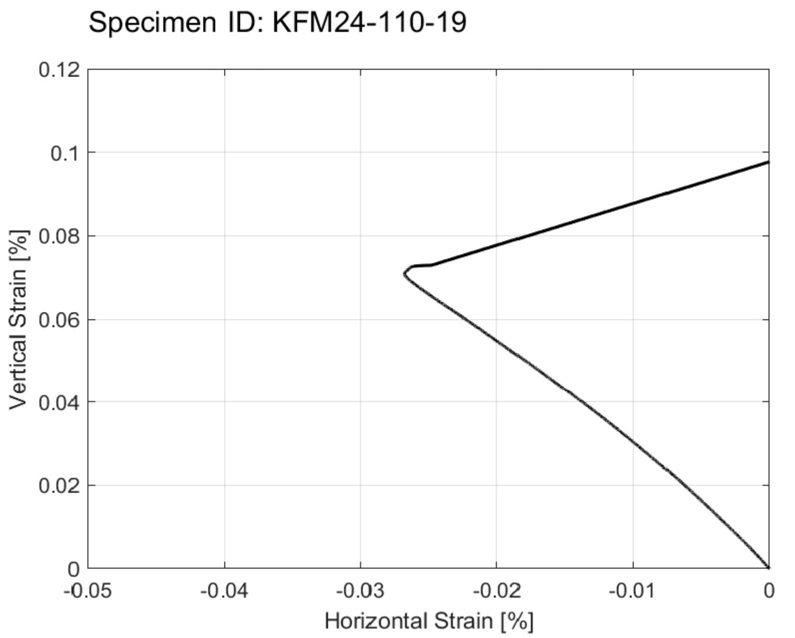
Before mechanical test

After mechanical test

Diameter (mm)	Height (mm)	Density (kg/m^3)	Tensile strength (MPa)
44.8	27.5	2656	11.7

Comments: None


Specimen ID: KFM24-110-19
Indirect tensile stress [MPa]
Strain [%]
Vertical
Horizontal
18
16
14
12
10
8
6
4
2
0
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12


Specimen ID: KFM24-110-19
Vertical Strain [%]
Horizontal Strain [%]
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.05
-0.04
-0.03
-0.02
-0.01
0

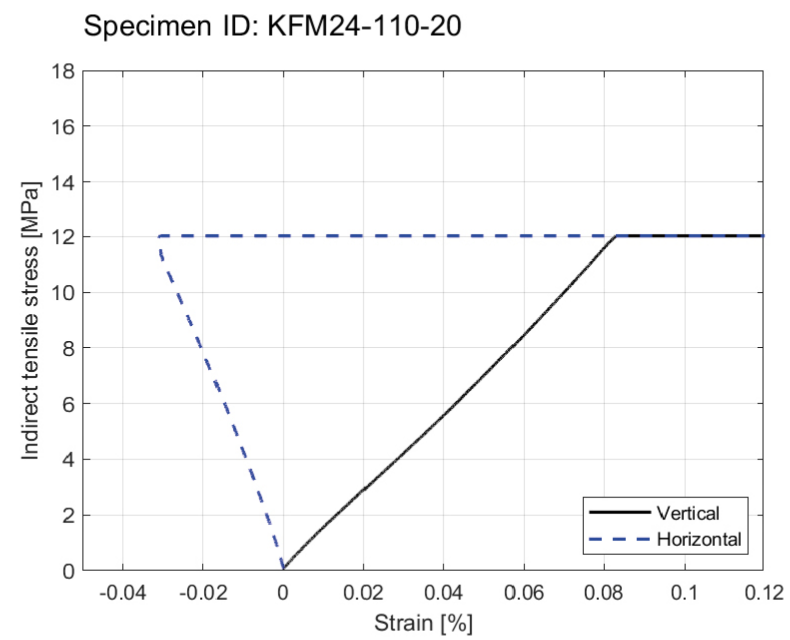
Specimen ID: KFM24-110-20

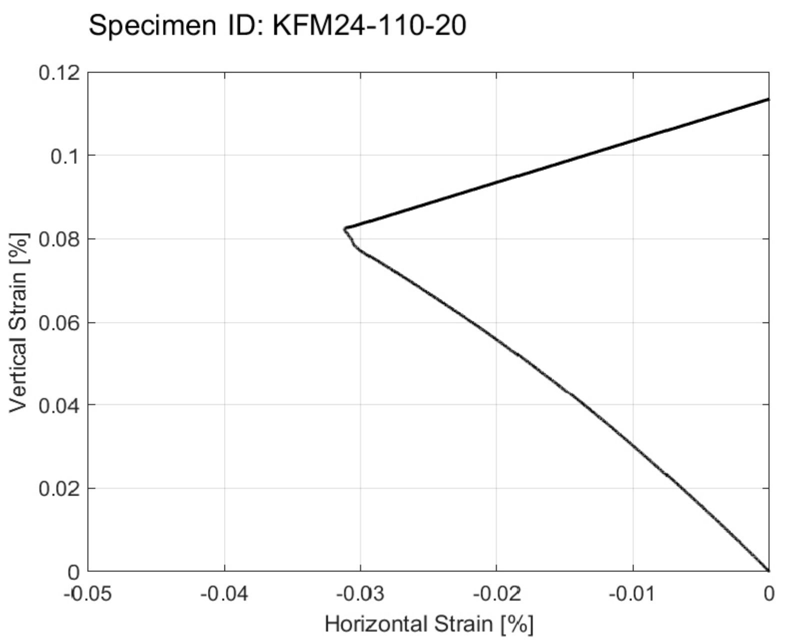
Before mechanical test

After mechanical test

Diameter (mm)	Height (mm)	Density (kg/m^3)	Tensile strength (MPa)
44.8	27.8	2650	12.0

Comments: None


Specimen ID: KFM24-110-20
Indirect tensile stress [MPa]
18
16
14
12
10
8
6
4
2
0
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12
Strain [%]
Vertical
Horizontal


Specimen ID: KFM24-110-20
Vertical Strain [%]
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.05
-0.04
-0.03
-0.02
-0.01
0
Horizontal Strain [%]

Specimen ID: KFM24-110-21

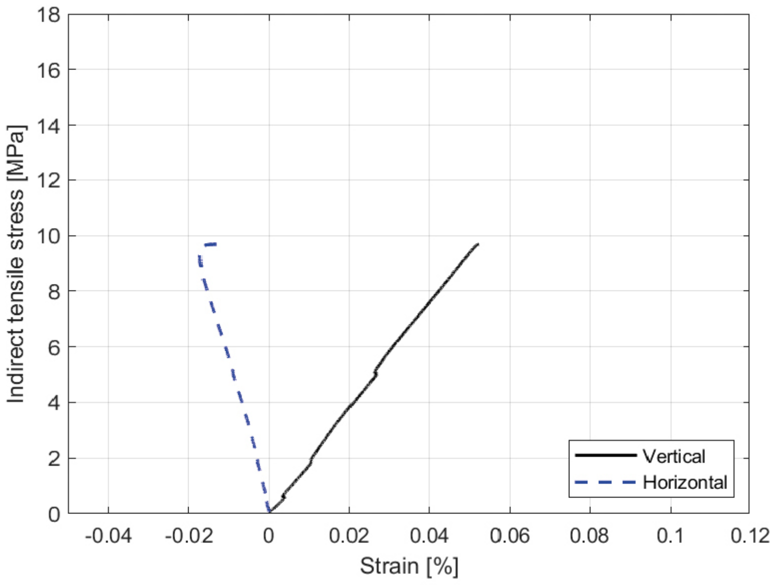
Before mechanical test

After mechanical test

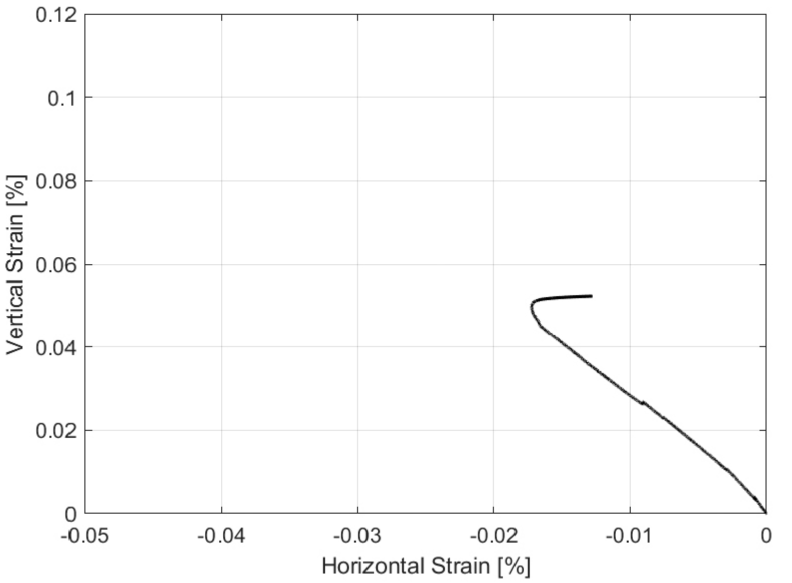
Diameter (mm)	**Height (mm)**	**Density (kg/m^3)**	**Tensile strength (MPa)**
44.8	27.9	2653	9.7

Comments: None

Specimen ID: KFM24-110-21



Specimen ID: KFM24-110-21



6.3.2 Results for the entire test series

The test results are shown in Tables 6-3 and 6-4 and in Figure 6-4.

Table 6-4. Results from density measurements and indirect tensile tests.

Identification	Density (kg/m^3)	Tensile strength (MPa)	Comments
KFM24-110-01	2668	13.9	loading perpendicular to foliation
KFM24-110-02	2650	16.5	loading perpendicular to foliation
KFM24-110-03	2660	13.9	loading perpendicular to foliation
KFM24-110-04	2665	12.1	loading perpendicular to foliation
KFM24-110-05	2658	14.4	loading perpendicular to foliation
KFM24-110-06	2648	11.7	loading perpendicular to foliation
KFM24-110-07	2667	14.3	loading perpendicular to foliation
KFM24-110-08	2675	13.4	loading perpendicular to foliation
KFM24-110-09	2665	14.2	loading perpendicular to foliation
KFM24-110-10	2668	14.8	loading perpendicular to foliation
KFM24-110-11	2664	15.3	loading perpendicular to foliation
KFM24-110-12	2667	15.1	loading perpendicular to foliation
KFM24-110-13	2663	15.9	loading perpendicular to foliation
KFM24-110-14	2659	15.0	loading perpendicular to foliation
KFM24-110-15	2659	14.6	loading perpendicular to foliation
KFM24-110-16	2660	13.4	loading perpendicular to foliation
KFM24-110-17	2653	12.2	loading perpendicular to foliation
KFM24-110-18	2657	14.4	loading perpendicular to foliation
KFM24-110-19	2656	11.7	loading perpendicular to foliation
KFM24-110-20	2650	12.0	loading perpendicular to foliation
KFM24-110-21	2653	9.7	loading perpendicular to foliation

Table 6-5. Calculated mean values and standard deviation (Std dev) of wet density and tensile strength.

	Density (kg/m^3)	Tensile strength (MPa)
Mean value	2660	13.7
Standard dev	7.1	1.7

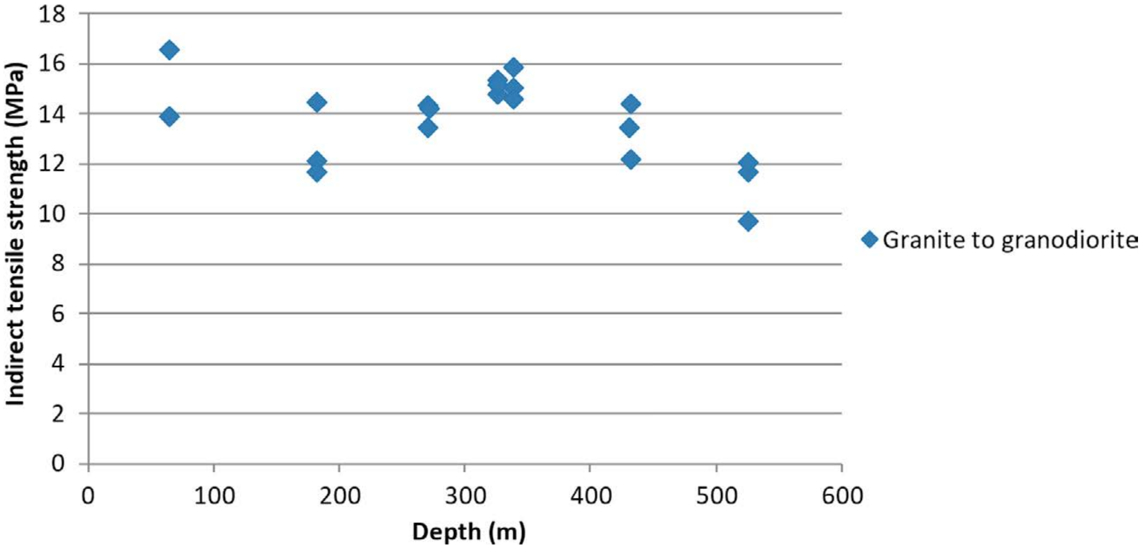


Figure 6-6. *Indirect tensile strength as a function of depth.*

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