Effects of test temperature and low temperature thermal cycling on the dynamic tensile strength of granitic rocks

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[2]**Abstract** This paper presents an experimental procedure for characterization of the granitic rocks on Mars-like environment. To gain better understanding of the drilling conditions on Mars, the dynamic tensile behavior of the two granitic rocks was studied using the Brazilian disc test and a Split Hopkinson Pressure Bar. The room temperature tests were performed on the specimens, which had gone through thermal cycling between room temperature and -70 °C for 0, 10, 15, and 20 cycles. In addition, the high strain rate Brazilian disc tests were carried out on the samples without the thermal cyclic loading at test temperatures of -30 °C, -50 °C, and -70 °C. Microscopy show that the rocks with different microstructures respond differently to cyclic thermal loading. However, decreasing the test temperature leads to an increasing of the tensile strength of the both studied rocks, and the softening of the rocks is observed for both rocks as the temperature reaches -70 °C. This paper presents a quantitative assessment of the effects of the thermal cyclic loading and temperature on the mechanical behavior of studied rocks in the Mars-like environment. The results of this work will bring new insight into the mechanical response of rock material in extreme environments.

Keywords: Granite, Dynamic Loading, High Strain Rate, Fractal Dimension, Low Temperature, Split Hopkinson Pressure Bar

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1- Introduction

In recent years, the exploration of Mars and Moon as alternative habitats for the humankind has attracted a great deal of attention. For instance, NASA has been rapidly increasing the number of missions for exploring Mars. During the 20th century, the number of missions was limited to four proposals and some limited mission designs. However, since the beginning of the 21st century, 29 missions have been completed (including unsuccessful missions) and there are currently 12 active missions (NASA 2019). This highlights the importance of increasing our knowledge and understanding of the environmental conditions on Mars to fulfil the final goal of sending humans to this planet. The environmental conditions on Mars are considerably harsher compared to Earth. For example, the minimum temperature recorded on Mars is -143 °C, while the maximum temperature reaches +35 °C with the mean temperature of about -63 °C (Jet Propulsion Laboratory 2007). Additionally, the atmosphere of Mars is mostly composed of carbon dioxide, argon and nitrogen, and the surface pressure is only about 0.00628 atm (Barlow 2008; Williams 2004). Consequently, tools that are usable on Earth might not be suitable for such harsh environmental conditions. Examples of such tools are drilling machines that have been optimized for the drilling conditions on Earth.

The major environmental concern in Mars is the temperature: the rocks are subjected to large temperature variations during the day (usually from +25 °C to -70 °C), which resembles the thermal cycling that materials, parts and components also in 'earthly' applications are occasionally exposed to, although seldom at such a low temperature range. Numerous studies have been conducted to analyze the effects of cyclic thermal loading and thaw-freeze cycles on the mechanical behavior of rocks (Mu et al. 2017; Eslami, Walbert et al 2018; Ma et al. 2018; DeKock et al. 2015; Zhou et al 2015; Jia et al 2015; Fener & Ince, 2015). Jia et al. (2015) studied the thermal fatigue and mechanical behavior of sandstone, which is used for highway constructions in China at temperatures of -10 °C to 20 °C. The cycles were repeated for 17 times with the freezing period of 12 hours. The cycles stopped at the count of 17 as the uniaxial tensile strength of rock reached almost to zero. While the ultimate tensile strength decreases almost by 100%, the compression strength of the rock decreases only by 35% after 17 cycles. In another study, Fener and Ince (2015) studied the effects of the freeze-thaw cycle (-18 °C to 32 °C) on the andesitic rocks, which are used in civil engineering applications. The samples went through as many as 30 cycles. Later on, the samples were tested at quasi-static conditions, and the authors reported that the tensile strength of rock decreased by 20% after 30 cycles, while the decrease of the compressive strength was about 25%. The authors also reported that the porosity of the tested rock increases by 25% after 30 cycles, which is in agreement with the decrease in the strength of the rock. De Kock et al. (2015) studied the dynamic fracture of Cenozoic miliolid limestone using x-ray computed microtomography after applying a thaw-freeze cycle. The cycle included 6 hours of freezing at -12 °C and 6 hours of thawing at 20 °C, and the maximum number of cycles was 84. The authors reported that the first fracture occurred during the second cycle and it continued growing during the freezing period. The reported fracture closed during the thaw period. After the fifth freezing period, the fracture reaches its critical size, which causes residual strain in the structure. However, the authors reported that when the samples are subjected to the freezing temperature of -5 °C, no clear damage to the structure occurs. The reason for this observation is that the probability of ice formation at small size samples decreases due to the lack of good nucleation surfaces. Therefore, instead of formation of ice, which causes strain in the structure, the water remains liquid in super cold condition (Sun & Scherer 2010).

It is understandable that analyzing different kind of rock materials that exist around the world and considering all the parameters, which affect the rock behavior under thaw-freeze cycle is a complicated and time-consuming procedure. Therefore, efforts have been put into simulating the rock behavior under such conditions. As an example, Ince and Fener (2016) developed a model to predict the behavior of pyroclastic rocks, which had been deteriorated after thaw-freeze cycle. The authors developed a statistical model for predicting the decrease of uniaxial compressive strength based on the rock's index-mechanical properties including dry density, ultrasonic velocity, point load strength, and slake-durability tests index values of the unweathered rock. In another work, Huang et al. (2018) developed a statistical damage constitutive model for rock behavior under thaw-freeze and loading condition. The model was developed to study the stability of the rock masses in cold regions. The authors expressed that the thaw-freeze damage by static elastic modulus and loading damage by statistical theory assuming the micro-unit strength satisfies the Weibull distribution and the maximum tensile strain yield criteria.

The authors concluded that the damage under thaw-freeze and loading causes structure softening in rock and using the developed model, the stability of the rock structure can analyzed and evaluated.

It is evident that considerable amount of effort has been put into understanding the rock behavior under cyclic thermal loading and thaw-freeze condition. However, almost all of the work has been related to the thaw-freeze cycle, which can be seen on the temperature range of the Earth. Moreover, the studies that have been conducted on Mars are limited to the surface material. Additionally, the numerical data and other information about the rocks' mechanical properties vary from one rock (and rock type) to another, being also valid only for the specific tested rocks and the applied testing conditions.

Additionally, to design efficient drill tools and systems, engineers need to know the rock strength and other properties under the drilling conditions. However, since direct experimental testing under drilling conditions is extremely complicated, various numerical constitutive models are currently being used. The construction of such models and validating the simulation results, however, rely on a good scientific understanding of the material behavior, as well as obtaining of solid experimental data for calibrating the material model parameters. The available literature concerning drilling on Mars is currently very limited. In one of the first attempts, the Mars Science Laboratory rover, *Curiosity*, successfully drilled three full depth holes into the Martian surface (Abbey et al., 2019). The holes were drilled in three different sites. The formations in the first two sites were reported as mudstone and the third site formation was made of sandstone. The areas on Mars, which potentially are composed of harder rocks, were avoided due to the possibility of the damaging the drilling tools on Curiosity (Abbey et al. 2019). Peters et al. (2017) studied the uniaxial compressive strength of the rocks drilled at Gale crater on Mars. The authors developed a methodology that uses the drill to indicate the uniaxial compressive strength of the rock through comparison with performance of identically assembled drill system in terrestrial samples of comparable sedimentary class. Additionally, the authors utilized the engineering data collected on Mars to calculate the percussive energy needed to maintain a prescribed rate of penetration and correlate that to rock strength. Unfortunately, there is no data available on the drilling condition when the holes were drilled such as temperature, atmosphere, or the pressure. For instance temperature has a strong influence on the drilling process. Liao et al. (2016) studied sandstone from room temperature to -40 °C. The authors showed that the strength of the sandstone increases as the temperature goes down to -30 °C, and cooling of the rock further down to -40 °C leads to the decrease in the strength of rock.

In addition to the temperature and drilling conditions, the microstructural features of the rock, such as the mineral composition, structure, grain size, microcracking, and porosity play an important role on the rock behavior in drilling and excavation conditions. Mineralogical characteristic is one of the main factors affecting the rock strength, and especially the content of quartz and feldspar have greater impact on the mechanical properties of rock compared to the other minerals. Tugrul and Zarif (1999) studied the correlation between mineralogical characteristic and the mechanical properties of granitic rocks. The authors concluded that the relationship between the physical properties and quartz and feldspar content is linear, but the content of quartz and feldspar can have positive or negative effects, which means that different minerals can have opposite effects on the strength of the rock. Another factor that affects the rock mechanical response is the rock structure and geomechanical quality. Pirkryl (2001) studied the area and perimeter of the grains using image analysis, and concluded that the degree of interlocking and the grain size homogeneity do not have an impact on the rock mechanical properties. Haney and Shakoor (1994) reported that the density of rock influences its strength and deformation properties. The same conclusion was made by Goodman (1989); however, this hypothesis was not confirmed by Pirkryl (2001). Moreover, the grain size has a significant influence on the mechanical response of rock. Wong et al. (1991) reported that the peak strength decreases with the inverse square root of the mean grain size. This conclusion is in accordance with the study conducted by Olsson (1974) and Brace (1961). Finally, the effect of porosity on the mechanical behavior of rocks have been studied by several researchers; Zhu et al (2010) showed that the compressive strength of the rock is scaled with the square root of the pore radius. In a similar work, Baud et al. (2014) concluded that in the rocks with equant pores, the compressive strength is controlled by porosity and pore radius and the ultimate compressive strength decreases with increasing amount of porosity.

It is evident that numerous factors ranging from testing condition, environmental condition, and rock properties itself affect the drillability of the rock. Therefore, there are many parameters, which have to be considered before starting a drilling project. Especially, if the drilling happens in the environment that we do not understand properly. This work focuses on the effects of the testing temperature and microstructure on the tensile strength of the studied rocks. The thermal loading cycles evidently affect the microstructures of the rock, create cracks, and deteriorate the overall structure and mechanical strength of the rock. To quantify these effects, two different rocks with two different microstructures were chosen for this study. Also a previously developed systematic research procedure (Mardoukhi et al. 2017) based on mechanical testing of rocks combined with optical microscopy and image analysis was used for enhancing our understanding of the mechanical behavior of rocks and to obtain data for the development of appropriate material models. The results of this work will bring new insights into the structure-property relationships of rock materials in extreme environments, especially at extremely low temperatures. In particular, the combination of mechanical testing, various microscopic investigations, and digital image-based analyses is believed to provide new scientifically important information about the rock behavior in the conditions prevailing on Mars.

2- Experimental procedure

Two types of granite, the Kuru Grey and Balmoral Red, were used in this study. Although there is very little knowledge of the granitic rocks in Mars (Wray et al., 2013), the hard granites on Earth can be considered to represent a difficult case for percussive drilling in Mars. The quasi-static compressive strengths are 184-218 MPa (Selonen et al. 2017) and 207 MPa (Selonen et al. 2016), whereas the open porosities were 0.44 and 0.38 for Kuru Grey and Balmoral Red, respectively. The quasi-static (Brazilian Disc) tensile strength of the Kuru Grey in tension is 11 ± 2 MPa, while the tensile strength of Balmoral Red 8 ± 2 MPa (Mardoukhi et al. 2017). Both studied rocks exhibit homogeneous distribution of the mineral without any visible texture. Therefore, it is considered that the mechanical properties of the rocks are isotropic. Detailed information about the petrological characteristic of Balmoral Red is available in (Selonen et al. 2016) and for Kuru Grey in (Selonen et al. 2017). Tables 1 and 2 show the mineral composition of the tested rocks.

Table 1 Mineral composition of the Balmoral Red granite (Selonen et al. 2016)

Table 2 Mineral composition of the Kuru Grey granite (Selonen et al. 2017)

The Brazilian Disc (BD) samples were cut out of the rock plate with the thickness of 21 mm and diameter of 40.5 mm. It should be noted that BD is not the only method to evaluate the mechanical properties of the brittle materials. Additionally, there are three other methods, i.e., dynamic direct tension method, the semi-circular bend (SBC) methods, and the spalling method. For more details about these methods the readers are referred to (Xia & Yao, 2015). The BD method was employed in this work due to its easy utilization and sample preparation. However, BD method has its own limitations as well. The main criteria for a successful BD test is that the sample should break first along the loading direction close to the center of the disc (Shewmon & Zackay 1961; Hudson, Brown et al. 1972). Additionally, the stress state is two-dimensional and tensile strength is not measured directly, but it is calculated from the axial loading. The assumption here is that the sample does not go through any plastic deformation.

Two types of Brazilian disc tests were conducted at the fixed impact speed of 10 m/s: 1) tests at room temperature (RT) on the specimens that had been thermally cycled between RT and -70 °C for different number of cycles, 2) and tests at RT, -30 °C, -50 °C and -70 °C using specimens without a thermal cycling pre-treatment. The impact speed corresponds to a typical impact speed of a percussive hammer, whereas the temperature range of the experiments were selected to approximate the upper range of temperatures on Mars (summer daily range from +20-70 °C). In the thermal cyclic loading, the samples were cooled down to -70 °C using a liquid nitrogen bath. An approximately 20 mm thick thermal shield made of aluminum oxide was used to prevent thermal shock to the specimens during cooling. The samples were kept in the bath long enough (~30 minutes) to assure a uniform temperature over the entire volume of the samples. When the temperature of the samples reached -70 °C, the samples were removed from the liquid nitrogen bath and let to warm up in air. A hole was drilled into dummy specimens of both tested rock types for measuring the temperature inside the samples, in addition to the temperature recorded from the surface of the specimens. The thermal cycles were applied for altogether 15 samples of each rock type. After each cycle, five samples were removed from further cycling. Therefore, after the thermal cyclic loading, four sets of samples that had undergone 0, 10, 15, and 20 cooling cycles were tested at dynamic loading conditions at room temperature. The duration of the cooling the samples to -70 °C is about 30 minutes and the duration of heating up to the room temperature is about 35 minutes.

Before applying the cyclic thermal loading, a liquid penetrant (Bycotest BP50) was applied on the surface of the samples to analyze the pattern of the surface cracks. After performing the thermal cyclic loading, the liquid penetrant was reapplied on the surface the samples to observe the changes to the crack pattern of the specimens. The images from the surfaces were taken by a LEICA CLS 150 XE stereomicroscope using a UV-light source. To obtain the fractal dimension, the images with the resolution of 2592 × 1944 pixels were imported to Matlab as RGB images and converted to binary images (or black and white). As the dominant color in the liquid penetrant is red, the threshold is set on "Red" color so that if a pixel has a "Red" color higher than the threshold value, the pixel is considered as a crack pixel, which is represented by digit "1", otherwise the pixel is "0". This creates a binary image, which shows the identified surface cracks. The fractal dimension of the surface crack pattern can then be calculated from the binary images using a box counting method in Matlab. In our previous work (Mardoukhi et al. 2017), we have described in details how to calculate the fractal dimension from microscope images, and that the fractal dimension analysis is an effective method to estimate the changes in the strength of rock materials, which have undergone the thermomechanical loading. However, the accuracy of this method is highly dependent on the image resolution as the pixels of the image are the grids used in box counting method. Therefore, the pixel might be altered by the background noise or the blurred neighboring pixel. For more details and information about this method, the readers are referred to (Feder, 1988; Li et al. 2009).

The high strain rate tests were performed using a Split Hopkinson Pressure Bar (SHPB) device. This is the same setup, which has been used in our previous work (Mardoukhi et al. 2017). The readers are referred to that work for the technical details of the setup. Schematic picture of the setup is shown in Figure 1.

The low temperature high strain rates tests were performed using cryogenic nitrogen gas to cool down the sample to the test temperature. The sample is placed between the bars and enclosed inside a cooling chamber together with short segments of the bars. The nitrogen gas is pumped to the cooling chamber through a heat exchanger, which is immersed in liquid nitrogen bath. As the nitrogen gas passes through the heat exchanger it becomes very cold, and can therefore be used to cool down the specimen. The specimen temperature is controlled by adjusting the gas flow rate into the chamber using a PID controlled piezoelectric proportional valve. The precision of the PID controller is ± 0.5 °C of the thermocouple reading. The sample temperature was recorded using a T-type thermocouple that was in contact with the top part of the specimen. To assure homogeneous temperature over the entire specimen, the samples were kept in the chamber for 15 minutes after reaching the required temperature.

Figure 1 Schematic picture of the Split Hopkinson Pressure Bar device at IMPACT Research Group of Tampere University.

A disc of a soft and deformable rubber with the thickness of 1 mm was used as the pulse shaper. Using pulse shaper in the BD tests is important as the stress state over the sample is two-dimensional, and therefore, the force balance at the boundaries does not necessary guarantee the dynamic equilibrium over the specimen. Accordingly, Dai et al. (Dai et al. 2010) have shown that the dynamic force equilibrium can be achieved using a pulse shaper in a BD test. Finally, a numerical dispersion correction based on the work of Gorham and Wu (Gorham & Wu 1997) was used to correct the possible changes in the signals due to the dispersion of the longitudinal stress waves as they travel in the bars.

Two Photron SA-X2 high-speed cameras were used to record the deformation of the specimens during dynamic loading of the room temperature tests. Later on the images were analyzed with Digital Image Correlation (DIC). As the rock surface itself does not provide enough contrast for the correlation algorithm, the surfaces of the samples were painted with a white base coat, and black speckles were applied on the surface using a permanent marker. The images were recorded at 160 kfps with the size of 250 x 176 pixels. The recorded images were analyzed using LaVision (DaVis10) 3D-DIC software with the subset size of 13 pixels and the step size of 5 pixels.

3- Results and discussion

3.1 - Characterization of the thermally loaded surfaces

Figures 2 and 3 show examples of the optical analysis used to characterize the cracks and their patterns on the surface of the specimens. Figures 2a and 2b are the original optical images obtained under UV light from Balmoral Red BD sample before and after 20 cycles of thermal loading. Figure 3a and 3b show the corresponding images for Kuru Grey. Figures 2c, 2d, 3c, and 3d show the processed images after thresholding the original images. The original images were imported to MATLAB as RGB images, where the color of each pixel is represented by three numbers, i.e., Red, Green, Blue. As the dominant color of the liquid penetrant is “Red”, the threshold is set on the color “Red”. If the pixel has the color “red” more than the value set for the threshold, that pixel is marked as a crack pixel with the value of “1”. If the value of the “Red” color is below the threshold limit, the pixel will be assigned a value of “0”. This creates a binary matrix that will be plotted as a map of identified surface cracks. It is evident that the fractal dimension obtained with this method is highly dependent on the threshold value and the resolution of the images. Therefore, when the map is created, the pattern of the cracks is checked by naked eye to decide whether it represents a real crack or not.

Figure 2 Optical images a) before and b) after 20 cycles of thermal loading, and the identified cracks c) before and d) after 20 cycles of thermal loading for Balmoral Red

Figure 3 Optical images a) before and b) after 20 cycles of thermal loading, and the identified cracks c) before and d) after 20 cycles of thermal loading for Kuru Grey

By comparing the images in Figs. 2 and 3 the difference between the surface crack patterns of Balmoral Red and Kuru Grey becomes evident. Before the cyclic thermal loading, the surface pattern of Balmoral Red consists of small cracks mainly at the grain boundaries. In case of Kuru Grey, in addition to the cracks, considerable amount of porosity can be seen on the surface. After the cyclic thermal loading, the surface crack pattern of Balmoral Red does not show any significant changes. However, for Kuru

Grey, some new cracks are visible on the surface after the fourth cycle of thermal loading but no significant changes were observed after the first, second, and the third cycles.

The fractal dimension was calculated following the process described above for 15 samples of both granites, i.e., five samples for each cycle of thermal loading. The average fractal dimension of Balmoral Red before the cyclic loading was 1.11 ± 0.11, while the fractal dimension for Kuru Grey before the thermal cyclic loading was 1.5 ± 0.1. The effect of the cyclic thermal loading on the crack patterns can be estimated from the fractal dimension after the cyclic loading normalized by its original value. Figure 4 shows the normalized fractal dimensions obtained for Balmoral Red and Kuru Grey as a function of number of thermal loading cycles.

Figure 4 Normalized fractal dimension for Balmoral Red and Kuru Grey as a function of number thermal loading cycles.

There seems to be a correlation between the change in fractal dimension of the samples before and after the cyclic thermal loading with their mechanical behavior, and specially the relative increase of fractal dimension of Kuru Grey has a great deal of importance in explaining the differences observed in mechanical responses of the two tested rock, which be explained later on.

3.2- Mechanical testing

The of the dynamic BD tests are shown in Fig. 5 for Balmoral Red samples as tensile stress versus time plots. The rock shows an average strength of 21 ± 3 MPa without any thermal loading cycle. After the cyclic thermal loading, the rock shows the tensile strength values of 21 ± 2 MPa, 21 ± 3 MPa, 21 ± 3 MPa, for the 10, 15, and 20 cycles, respectively. Therefore, the cyclic thermal loading does not have any effect on the strength of Balmoral red.

Figure 5 High strain rate test results showing the tensile stress as a function of time for Balmoral Red samples a) without any cyclic thermal loading, after b) 10 cycles, c) 15 cycles, d) 20 cycles.

The situation is different for Kuru Grey. The average room temperature tensile strength of Kuru Grey without any prior thermal loading is 28 ± 2 MPa. The strength of the rock does not change noticeably for the first two set cycles, and the strength of rock shows the value of 30 ± 2 MPa and 29 ± 2 MPa for the 10 and 15 cycles, respectively. Only at the 20th cycle, the strength of the rock drops about 17% and the strength of the rock decreases to 23 ± 2 MPa. The behavior of the rock does not change after the thermal loading cycles, and only the strength decreases. However, as the strength does not decrease until the 20th cycle, it is evident the rock requires higher number of thermal loading cycles to develop more cracks in its structure to facilitate the fracture. Nonetheless, the difference in behavior of the two rocks can be explained by considering the differences in the their structures. The fractal dimension of Balmoral Red did not change after the thermal cyclic loading which indicated that the number of cracks in the structure of the rock did not increase. On the other hand, in case of Kuru Grey, the fractal dimension increased after 15 cycles, indicating an increase in the number of cracks and a change in the interconnectivity of the cracks. Despite this increase, the strength of the rock does not decrease significantly. This means that the increase in the number of cracks at the 15^{th} cycle is not yet enough to expedite the fracture of the rock specimen and therefore, no significant change in the strength of the rock was observed. It should be noted that in this study only the maximum of 20 cycles of thermal loading was performed on the specimens, and the behavior of the studied rocks can change if the number of thermal cycles is further increased.

The engineering strain in the direction perpendicular to the loading direction prior to fracture was measured with LaVision (Davis10) 3D-DIC software by placing a virtual extensometer with a length of 10 mm at the center of the specimens (See Fig. 6). The results of the digital image correlation show that the strain prior to fracture of the Balmoral Red does not change for any of the thermally cycled samples, but for Kuru Grey, the strain prior to fracture decreases for the samples that have been thermally loaded for at least 15 cycles. Figure 6 shows an example of DIC images and Figure 7 shows the strain prior to fracture of the tested rocks as the number of thermal loading cycles. More detailed information and discussions about the strain fields and their development observed in the dynamic Brazilian Disc specimens can be found in our previous work (Mardoukhi et al. 2017).

Figure 6 An example of the DIC analysis for a Balmoral Red sample without any cyclic thermal loading tested at room temperature; a) first image with virtual extensometer, b) before loading, c) start of the loading d) prior to fracture, and e) after fracture.

Figure 7 Strain prior to fracture as a function of thermal loading cycles for Balmoral Red and Kuru Grey.

The results of the dynamic BD tests at different temperatures are shown in Figures 8 and 9 for Balmoral Red and Kuru Grey, respectively. The tests were carried out for specimens without any thermal cycling. The average tensile strength obtained for five Balmoral Red samples tested at room temperature is 21 ± 3 MPa. However, as the temperature decreases down to -70 °C, the tensile strength of the rock starts to increase. The average tensile strength measured for Balmoral Red is 32 ± 2, 31 ± 2, and 26 ± 3 MPa at -30 °C, -50 °C, and -70 °C, respectively. Similar behavior is observed for Kuru Grey. The tensile strength of the rock at room temperature is 28 ± 2 MPa. By decreasing the temperature down to -50 °C, the tensile strength of the rock starts to increase and remains constant down to -70 °C. The tensile strength measured for Kuru Grey are 35 ± , 38 ±3, and 37 ± 3 MPa at -30 °C, -50 °C, and -70 °C, respectively.

Figure 8 High strain rate test results showing the tensile stress as a function of time for Balmoral Red at a) room temperature, b) -30 °C, c) -50 °C, and d) -70 °C.

Figure 9 High strain rate test results showing the tensile stress as a function of time for Kuru Grey at a) room temperature, b) -30 °C, c) -50 °C, and d) -70 °C.

Figure 10 shows the tensile strength of the rocks as a function of testing temperature. The strength of both rocks tends to increase as the temperature decreases. The softening of the rocks at low temperature has been reported by Liao et al. (2016), which occurs for sandstone stone at -40 °C. The softening of the rock at -70 °C is more pronounced for Balmoral Red compared to Kuru Grey, for which the strength remains constant. In general, it seems that as the temperature decreases, the rocks are stronger due to the compaction of the microstructure, and especially the compaction of the microcracks and their tips. However, further compaction of the microstructure by decreasing the temperature may cause internal stresses in the microstructure due to different thermal expansion coefficients with different thermoelastic moduli, which could lead to the formation of cracks, easier propagation of cracks and consequently lower strength of the rocks (Kranz, 1983).

Figure 10 Tensile strength of Balmoral Red and Kuru Grey as a function of testing temperature.

4- Concluding remarks

- Two types of Brazilian disc tests were conducted at the fixed impact speed of 10 m/s: room temperature tests on the specimens that had been thermally cycled between RT and -70 °C for different number of cycles, and tests at RT, -30 °C, -50 °C and -70 °C using specimens without a thermal cycling pre-treatment.
- The results suggest that the thermal cycling does not have a strong effect on the surface cracking nor the dynamic behavior of Balmoral Red granite. Instead, a clear effect could be observed for Kuru Grey granite, as the tensile strength at room temperature of this rock started to decrease after the application of a sufficient number of thermal loading cycles. The decrease however, was marked only after the 20^{th} cycle.
- The fractal dimension of Balmoral Red does not change after any number of cycles applied in this work, whereas in the case of Kuru Grey, the fractal dimension starts to increase from the 15^{th} cycle on, indicating an increase in the number of cracks and a change in the interconnectivity of the cracks. The increase in the number of cracks observed after the fourth cycle however, is not yet enough to expedite the fracture of the rock specimen and therefore, no significant change in the strength of the rock was observed.
- The results of digital image correlation show that the strain prior to fracture of the Balmoral Red does not change for any of the thermally cycled samples, but in the case of Kuru Grey, the strain prior to fracture decreases for the samples that have been thermally loaded for at least four cycles. The reason for this difference between Balmoral Red and Kuru Grey can be found from the difference in the microstructure of the two rocks: the porosity of Kuru Grey is considerably higher than that of Balmoral Red, which makes it more prone to cracking as the pores can act as nucleation sites for the cracks during the contraction and expansion caused by the thermal cycling.

- The results from the tests at low temperatures show that the strength of the rock increases as the temperature reaches -50 °C. Cooling the rock further to -70 ° results in the decrease in strength of the Balmoral Red, but the strength of the Kuru Gray stays approximately constant. The reason for the increase of the strength is that as the temperature goes down, the microstructure of rocks become more compact and some of the crack tips may be closed due to the thermal shrinkage. Further compaction of the structure causes internal stresses, which leads to the formation more cracks and consequently, the strength of the rocks starts to decrease.
- The more noticeable decrease of strength for Balmoral red compared to Kuru Grey can be explained by the difference in the microstructure of the two rocks. More porosity in Kuru Grey structure provides more space during the compaction of the structure at subzero temperature. On the other hand, the microstructure of Balmoral Red does not contain as high amount of porosity as Kuru Grey. Therefore, further compaction of its microstructure results in the weakening of the structure.
- The results suggest that the temperature has an effect on the mechanical response of rock in drilling condition. It appears that as the rock gets colder, the amount of energy to break rock increases. On the other hand, it seems that thermal cyclic loading of the rock eventually leads to the deterioration of rock and decrease its strength. Therefore, on the drilling environments such as Mars, where the rocks are subjected to constant thermal loading at the surface and are cold beneath the surface, the drilling condition might be complicated, i.e., soft rocks at the surface and harder rocks under that layer. Consequently, it is understandable that the drilling in such environment requires careful planning and more detailed studies.

As it was mentioned before, this series of tests provides the opportunity to study the mechanical behavior of the rocks at extreme conditions like those observed in Mars or other planets and moons in the laboratory scale. One of the main interests in percussive drilling is to create bigger chips with the minimum possible force and energy. Based on this work, granitic rocks can have different behaviors when are subjected to cyclic thermal loading depending on their microstructure. However, the temperature of the rock plays an important role on the energy required to fracture the rock. Cooling the rock down to -50 °C increases the strength of the rock, however, further cooling of the rock down to -70 °C leads to the decrease of its strength. However, it should be noted that even though the strength of the rock decreases, it still has higher strength compared to its strength at room temperature. Nevertheless, the tests performed at this study were limited to only 20 thermal loading cycles and selected temperatures. In order to be able to fully characterize the rock behavior at the low temperatures condition, more experiments on the rocks with temperatures beside used in this study should be carried out. Additionally, X-ray CT scans and electron microscopy analysis will be included in the future work to characterize the formation and propagation of the cracks in microstructure due to the thermal loading and freezing of the rock. Finally, the experiments should be complemented by microstructure based FEM modeling where the physical and thermal properties, especially the thermal expansion coefficients, of the different constituent phases could be taken into account, and the mechanical stresses caused by the thermal cycling and overall changes in temperature could be quantitatively evaluated.

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