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THERMAL AND CRYOGENIC FRACTURE INTERACTIONS IN GRANITE: FRACTURE TOUGHNESS TESTS FOR GEOTHERMAL DEVELOPMENT

[1]D.T. Begaliyev, [1]N.M. Zhumagaliyev, [1]A.S. Kupeshova, [2]A.T. Zholbasarova, [1]A.B. Kydrashov, [1]B.Zh. Burkhanov, [3]A.R. Abdiev

[1]NJSC "West Kazakhstan Agrarian and Technical University named after Zhangir khan",Uralsk, Kazakhstan,
[2]NJSC "Caspian State University of Technologies and Engineering named after S.Yessenov", Aktau, Kazakhstan,
[3]Kyrgyz Mining and Metallurgical Institute named after academician U. Asanaliev, Bishkek, Kyrgyzstan

Corresponding authors: dastan.begaliyev@wkau.kz, a.kydrashov@mail.ru

The use of liquid nitrogen (LN_2) as a freezing agent has been shown to help enhance the permeability of the rock, making it easier for fluids to pass through, which improves how much water or steam can flow from the reservoir. This is especially useful in Hot Dry Rock (HDR) systems. This study looks at how exposing granite to low temperatures affects its strength after it has been cooled down after being heated. Fracture Toughness Tests were done on granite samples after they were first baked at different temperatures from 100 °C to 400 °C before being quickly cooled with LN_2 to copy what happens when something gets suddenly cooled quickly.

The tested granite samples were taken from a place that is around 50 km away from Astana, in the Akmola region of Kazakhstan. Experimental measurements helped find important mechanical values like the maximum load the sample could handle, how much stress builds up at the tip of the crack, and how much energy it takes to make the sample break. The results show that using liquid nitrogen makes it much easier for cracks to start and spread in the sample, and doing LN_2 treatment at higher pre-treatment temperatures makes it happen even faster. A consistent decrease in both the stress intensity factor and fracture energy as the temperature went up could be seen. These findings show that using LN_2 to freeze and crack the rocks can be a useful way to help boost the flow of geothermal energy from certain types of hard rocks.

Keywords: geothermal energy, Kazakhstan, cryogenic fracturing, liquid nitrogen, fracture toughness test, intensity factor, fracture energy, granite, HDR(hot dry rocks).

ГРАНИТТЕГІ ТЕРМИЯЛЫҚ ЖӘНЕ КРИОГЕНДІК СЫНЫҚТАРДЫҢ ӨЗАРА ӘРЕКЕТТЕСУІ: ГЕОТЕРМИЯЛЫҚ ДАМУҒА АРНАЛҒАН СЫНЫҚТАРДЫҢ БЕРІКТІГІН СЫНАУ

[1]Д.Т. Бегалиев, [1]Н.М. Жумагалиева, [1]А.С. Купешова, [2]А.Т. Жолбасарова, [1]А.Б. Кыдрашов, [1]Б.Ж. Бурханов, [3]А.Р. Абдиев

[1]«Жәңгір хан атындағы Батыс Қазақстан аграрлық-техникалық университеті» КеАҚ ,Орал, Қазақстан,
[2]«Ш. Есенов атындағы Каспий технологиялар және инжиниринг университеті» КеАҚ, Ақтау, Қазақстан,
[3]Академик У. Асаналиев атындағы Қырғыз тау-кен металлургиялық институты, Бішкек, Қырғызстан,
e-mail: dastan.begaliyev@wkau.kz, a.kydrashov@mail.ru

Сұйық азотты (LN_2) мұздату агенті ретінде пайдалану геотермалды потенциалы бар тау жыныстарының өткізгіштігін арттыруға көмектесетіні дәлелденді. Бұл сұйықтықтардың өтуін жеңілдетеді және сол арқылы жер асты резервуарларынан су немесе бу шығу мүмкіндігін жақсартады. Ондай тау жыныстары әдетте ыстық құрғақ күйде болады (hot dry rock, HDR). Бұл зерттеу гранитті қыздырып, оны сұйық азотпен тез арада салқындатудан кейін оның беріктігіне қалай әсер ететінін қарастырады. Бұл жүргізілген сынақтар 100 °C-тан 400 °C-қа дейінгі әртүрлі температурада қыздырылған граниттерді қамтыды.

Сыналған гранит үлгілері Астанадан шамамен 50 км қашықтықта, Қазақстанның Ақмола облысында орналасқан жерден алынды. Эксперименттік өлшеулер гранит тастарының көтере алатын максималды жүктеуін, жарықшақтың ұшында қанша қысым жиналатыны және үлгіні бұзу үшін

қанша энергия қажет болатыны сияқты маңызды механикалық мәндерді табуға көмектесті. Нәтижелер сұйық азотты пайдалану гранит тастарындағы жарықтардың пайда болуын және таралуын айтарлықтай жеңілдететінін, ал өңдеуге дейінгі жоғарырақ температурада қыздырылуы және сұйық азотқа батырылуы оны одан да жылдамырақ ететінін көрсетеді. Температура көтерілген сайын қысым қарқындылығы факторының да, сыну энергиясының да тұрақты төмендеуін байқауға болады. Бұл нәтижелер құрғақ ыстық тау жыныстарын мұздату және жару үшін LN_2 пайдалану қатты жыныстардың белгілі бір түрлерінен геотермалдық энергия ағынын арттырудың пайдалы әдісі болуы мүмкін екенін көрсетеді.

Түйін сөздер: геотермалды энергия, Қазақстан, криогендік жару, сұйық азот, жарықшаққа төзімділік сынағы, қарқындылық коэффициенті, жарықшақ энергиясы, гранит, HDR (құрғақ ыстық жыныстар).

ВЗАИМОДЕЙСТВИЕ ТЕРМИЧЕСКОГО И КРИОГЕННОГО РАЗРУШЕНИЯ ГРАНИТА: ИСПЫТАНИЯ НА ТРЕЩИНОСТОЙКОСТЬ ПРИ РАЗРАБОТКЕ ГЕОТЕРМАЛЬНЫХ МЕСТОРОЖДЕНИЙ

[1]Д.Т. Бегалиев✉, [1]Н.М. Жумагалиева, [1]А.С. Купешова, [2]А.Т. Жолбасарова, [1]А.Б. Кыдрашов✉, [1]Б.Ж. Бурханов, [3]А.Р. Абдиев

[1]НАО «Западно-Казахстанский аграрно-технический университет им. Жангир хана», Уральск, Казахстан,
[2]НАО «Каспийский университет технологии и инжиниринга им. Ш.Есенова»,Актау, Казахстан,
[3]Кыргызский горно-металлургический институт им. академика У.Асаналиева ,Бишкек, Кыргызстан,
e-mail: dastan.begaliyev@wkau.kz, a.kydrashov@mail.ru

Было доказано, что использование жидкого азота (LN_2) в качестве замораживающего агента помогает повысить проницаемость породы, облегчая прохождение жидкостей, что позволяет увеличить объем воды или пара, которые могут вытекать из резервуара. Это особенно полезно для горячих сухих горных пород (hot dry rock, HDR). В этом исследовании рассматривается влияние воздействия низких температур на прочность гранита после его охлаждения после нагрева. Испытания на трещиностойкость были проведены на образцах гранита после того, как они были сначала нагреты при различных температурах от 100 °C до 400 °C, а затем быстро охлаждены с помощью LN_2, чтобы воспроизвести термошок, когда что-то внезапно быстро охлаждается.

Протестированные образцы гранита были взяты из места, расположенного примерно в 50 км от Астаны, в Акмолинской области Казахстана. Экспериментальные измерения помогли определить важные механические параметры, такие как максимальная нагрузка, которую может выдержать образец, величина напряжения, возникающего на вершине трещины, и количество энергии, затрачиваемой на разрушение образца. Результаты показывают, что использование жидкого азота значительно облегчает образование и распространение трещин в образце, а обработка LN_2 при более высоких температурах предварительной обработки позволяет сделать это еще быстрее. С повышением температуры наблюдалось последовательное снижение коэффициента интенсивности напряжений и энергии разрушения. Эти результаты показывают, что использование LN_2 для замораживания и растрескивания горных пород может быть полезным способом увеличения потока геотермальной энергии из определенных типов твердых пород.

Ключевые слова: геотермальная энергия, Казахстан, криогенный разрыв, жидкий азот, испытание на устойчивость к разрушению, коэффициент интенсивности напряжений, энергия разрушения, гранит, HDR (горячие сухие породы).

Introduction. With the world looking to reduce emissions and use environmentally friendly energy, geothermal power has become vital for making this happen. Interest has grown in Hot Dry Rock (HDR) formations due to their ability to provide temperatures that range from 150 °C to over

500°C at depths of around 5000-6000 meters [1-4]. Innovative though they are, HDR systems do not work as well for business purposes due to their naturally low ability to transfer heat. As a result, it is important to apply new stimulation methods to unleash all the advantages of these reservoirs [5-9].

One popular trend now uses liquid nitrogen (LN_2) in what is known as cryogenic fracturing. LN_2-based stimulation uses the low temperature and pressure conditions at -196 °C to quickly contract high-temperature rock. The heat shock leads to the development of many small fractures that aid the movement of fluids within the rock [10-14]. Unlike traditional hydraulic fracturing which can lead to chemical pollution and wastes a lot of water, LN_2 stimulation is both cleaner and more sustainable. The brittleness of granite at low temperatures allows it to form many fractures, contributing to the overall development of complex systems [15-20].

This research focuses on checking how granite from the Akmola region in Kazakhstan responds when it is subjected to cryogenic fracturing. For our experiment, granite samples were first heated to different high temperatures and rapidly cooled with liquid nitrogen. Then, the fracture toughness was tested to measure the thermal damage done. Cracking behavior was investigated by using fracture energy and mode I stress intensity factor at different thermal conditions. This study aims to find better, more environmentally friendly ways to stimulate wells by examining the effectiveness of using liquid nitrogen on HDR geothermal reservoirs.

Materials and methods. Granite samples were collected from rocks that stick out of the ground not far from Vyacheslavka in Akmola, Kazakhstan. For the fracture toughness tests, the samples were made into a semicircular shape, which can be seen in Figure 1. Prior to testing, all the specimens were dried out in an oven for about 24 hours at 50 degrees to get rid of any moisture on their surface. They were then put in a furnace and heated for two hours at 100, 200, and 400 degrees Celsius. After heating, the samples were lowered straight into a liquid nitrogen bath for an hour to simulate exposure to cryogenic temperatures (such as those used in space). To make sure there was no more moisture left, the samples were dried again at 50 C for an hour. The fracture toughness tests were then carried out with the GCTS UCT-1000 testing machine, which you can see on the right in Figure 1.

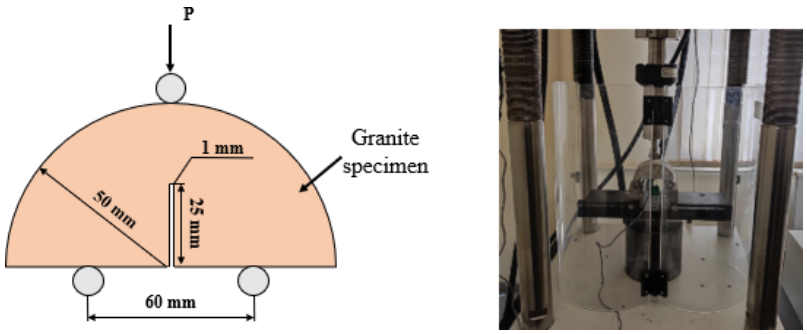


Fig.1 - Granite specimen dimensions and setup

Results and discussion. The graph in Figure 2 shows the results of fracture toughness tests done on granite after subjecting them to different hot and cold temperatures. The sample only treated at 50 °C acted as the reference, and the other samples were heated to 100 °C, 200 °C, and 400 °C before being frozen in liquid nitrogen for one hour. Each test was duplicated twice to improve the reliability of the data and cut down on measurement mistakes. The specimens without any treatment reached their highest peak load at 50 °C, while peak load in the others became lower with both thermal and cryogenic treatment. With temperatures going up during preheating, more and larger microcracking

was found. Elevated temperatures caused more damage to the material, which LN_2 only made worse, resulting in a drop in its ability to hold weight.

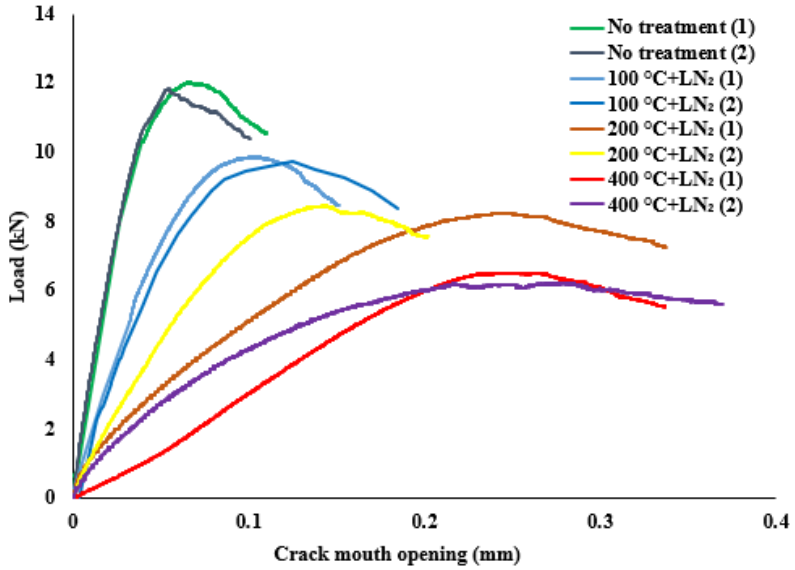


Fig.2 - Load vs crack mouth opening curves from fracture toughness tests

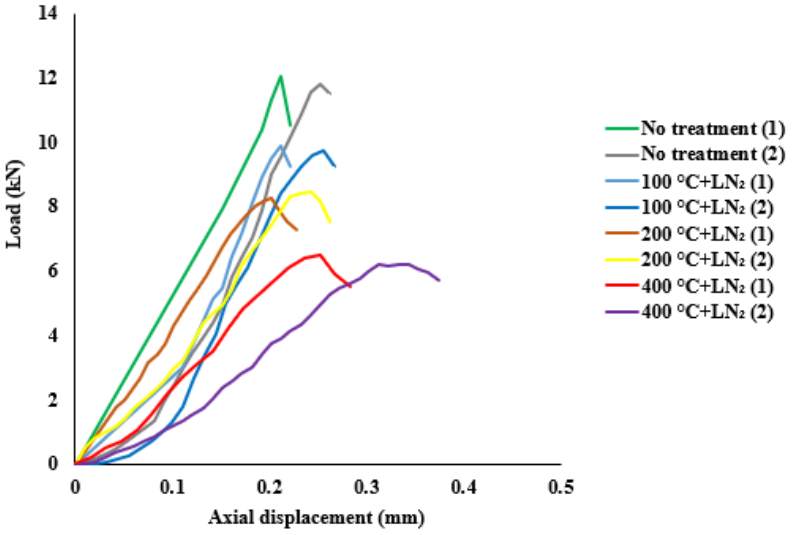


Fig.3 - Load vs axial displacement curves after fracture toughness tests

The same fracture toughness test samples showed the load-displacement curves that can be seen in Figure 3. The untreated samples at 50 C had the biggest strengths and could handle more pressure in the experiments, since their graphs showed steeper curves. In contrast, when samples were put through a mix of heat and freezing, they were less strong when stretched and moved more before breaking, especially in the samples that were heated up to 400°C and then cooled down with liquid nitrogen. This behavior shows that over time, the material gets weaker because of things like expansion when it gets hot, the development of tiny cracks, and shrinkage when it gets cold. As these effects add up,

the stone slowly gets softer and less sturdy, which then results in it being less able to hold up to tension.

The results of Figure 4 show the stress intensity factor results from fracture toughness tests, with each pre-treatment compared to the reference group preheated at 50 °C. When the pre-heating temperature is raised, the material strength is seen to decrease, indicated by a drop in peak stress intensity factors. In both experiments, the sharpest drop in the value of stress intensity factor was found under the 400 °C + LN_2 condition, with a value of 0.91 MPa·m$^{1\ \ 2}$. Cooling the granite rapidly using LN_2 after heating it to a high temperature turned out to be the best type of experiment for inflicting internal damage on the sample. Matching results between both experiments and the trend seen support the accuracy of the findings.

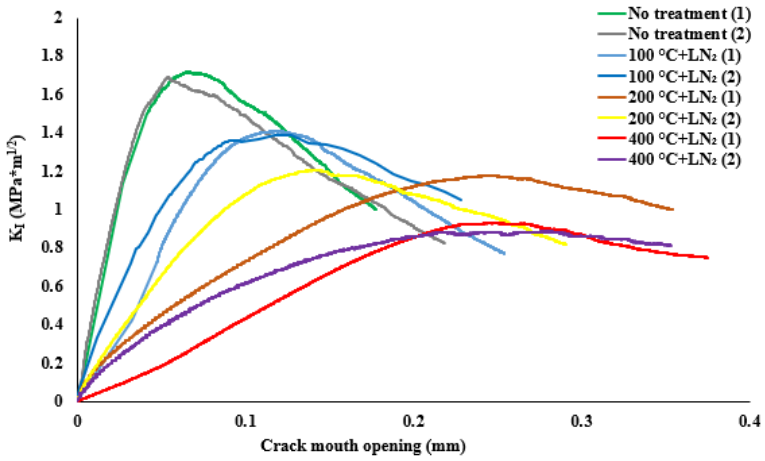


Fig.4 - Mode I stress intensity factor vs crack mouth opening curves after fracture toughness tests

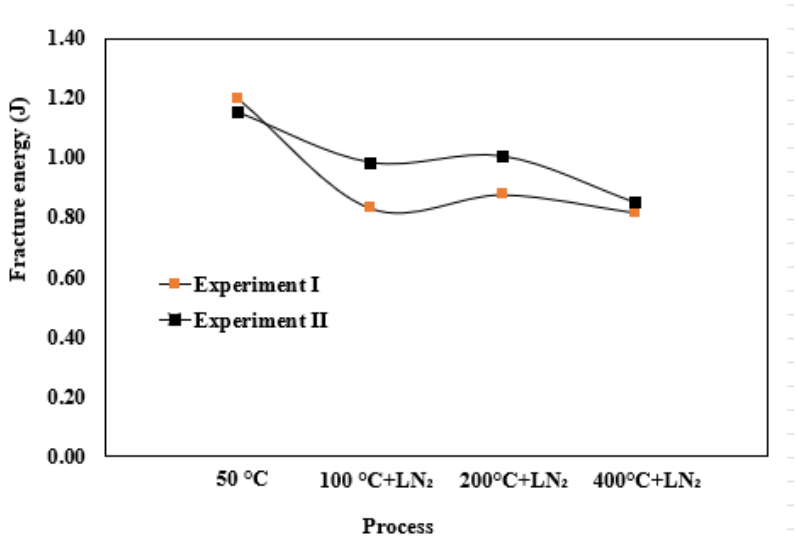


Fig.5 - Fracture energy vs process after fracture toughness tests

Figure 5 highlights the difference in mechanical behavior of granite when subjected to thermal and cryogenic loading, by using fracture energy as a measure. Fracture energy shows the total effort needed to break apart a sample of rock and is a sign of toughness. The best fracture-resistance was seen

in the granite samples preheated only to 50 °C, as they were still largely intact and without damage.

Fracture energy was reduced by an average of 0.906 J when the granite was heated at 100 °C and then quickly cooled with LN_2 in the first two experimental trials. It seems that when rocks go through a brief heating period and then a sudden, extreme cooling, it causes internal fractures that lower the strength of the rock. If thermal pre-treatment is made more severe, the material becomes more vulnerable to cracking and breaking. Compressive tests for samples treated at 200 °C and then exposed to LN_2 resulted in a fracture energy of 0.939 J, showing that the material had grown more fragile.

Among all cases, the ones heated at 400°C and cooled with LN_2 showed the lowest fracture energy of 0.831 J. The significant change from the reference condition means that major internal damage and a loss of bonding between materials occurred as a result of the thermal and cryogenic stress during the test. All in all, the results clearly show that higher preheat temperatures before LN_2 treatment result in considerably softer granite, proving the method's success in improving fracturing of rocks for geothermal use.

Table 1 displays the fracture toughness results of granite specimens put through different thermal shock conditions. Without any treatment, the K_I factor was measured at 1.71 MPa·m¹ ². Still, raising the temperature of the specimens and then suddenly lowering it with liquid nitrogen caused an obvious drop in their fracture toughness. There was a drop of 17.8% in the K_I value in both trials when the temperature was set to 100 °C and LN_2 was added. Significant decreases in content occurred at higher degrees of preheating. The first and second trials both saw decreases of 31.4% and 28.4% after using 200 °C + LN_2. Using 400 °C + LN_2 caused the most noticeable declines, with a change of 45.8% and 47.4% in trials 1 and 2, respectively. We clearly see a certain pattern in the results. A higher temperature during the preheating stage tends to bring down the fracture toughness of granite before it is treated with LN_2. The research confirms that the level of damage to rocks after LN_2 exposure increases along with the duration of preheating, showing a proper relationship between the damage caused by long-term exposure and high-temperature conditions.

Table 1 - Effect of increase in temperature along with LN_2 to the peak values of mode I intensity factor values

Specimen	Treatment	Peak value of KI	Stepwise Difference	Difference from Baseline	Average value of KI peaks
		(MPa*m$^{1/2}$)	(%)	(%)	(MPa*m$^{1/2}$)
1	No	1.72	-	-	1.71
2		1.69			
1	100+LN2	1.41	-17.8	-17.8	1.40
2		1.39	-17.7	-17.7	
1	200+LN2	1.18	-16.5	-31.4	1.19
2		1.21	-13.1	-28.4	
1	400+LN2	0.93	-21.0	-45.8	0.91
2		0.89	-26.5	-47.4	

Conclusion. Akmola granite samples were studied through an experimental process using liquid nitrogen (LN_2) temperatures to see how it affected preconditioned granite. The evaluation

involved carrying out fracture toughness tests, checking the load-displacement curve, and getting readings of the fracture energy and stress intensity factors. The key findings from the study are as follows:

- Preheating over 400 °C with LN_2 caused a continuous reduction in load-bearing, and the group with the highest preheated temperature showed the least ability to support a high load.

- When materials were pre-treated at higher temperatures along with liquid nitrogen, the amount of fracture energy they absorbed reduced. Combining heat and cryogenic cracking greatly reduced the amount of effort required to overcome the resistance of the granite.

- Calculations of K_I, a standard measure for toughness, revealed that LN_2 makes cracks grow more effectively at higher preheating temperatures.

- All of the samples proved to fail in the same qualitative way during treatment under LN_2, still variations were noticed in the fracture energy and toughness at different temperature levels.

The results taken together show that exposing granite to heat and flash-freezing it significantly reduces its strength, making it a useful strategy for helping break up rocks in geothermal energy production.

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Information about the authors

Begaliyev D.T.- NJSC “West Kazakhstan Agrarian and Technical University named after Zhangir khan”, master of technical sciences, Uralsk, Kazakhstan, dastan.begaliyev@wkau.kz;

Zhumagaliyeva N.M.- NJSC “West Kazakhstan Agrarian and Technical University named after Zhangir khan”, master of technical sciences, Uralsk, Kazakhstan, zhumagaliyeva.nurzhamal@inbox.ru;

Kupeshova A.S.- NJSC “West Kazakhstan Agrarian and Technical University named after Zhangir khan”, senior lecturer, Uralsk, Kazakhstan, kupeshova.altynay@mail.ru;

Zholbasarova A.T.- NJSC “Caspian State University of Technologies and Engineering named after S.Yessenov”, candidate of technical sciences, associate professor, Aktau, Kazakhstan, akshyryn.zholbassarova@yu.edu.kz;

Kydrashov A.B.- NJSC “West Kazakhstan Agrarian and Technical University named after Zhangir khan”, PhD doctor, associate professor, Uralsk, Kazakhstan, a.kydrashov@mail.ru;

Burkhanov B.Zh.- NJSC “West Kazakhstan Agrarian and Technical University named after Zhangir khan”, candidate of technical sciences, associate professor, Uralsk, Kazakhstan, aruka73@mail.ru;

Abdiev A.R.- Kyrgyz Mining and Metallurgical Institute named after academician U.Asanalieva, doctor of technical sciences, professor, Bishkek, Kyrgyzstan, arstanbek.abdiev@kstu.kg.