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DELIVERABLE D2.3

Laboratory testing and modelling of direct laser and gas interaction with rocks

Lead Beneficiary: FhG-IAPT

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ABBREVIATIONS AND GLOSSARY OF ACRONYMS

Acronym	Extended definition
D	Deliverable
IAPT	Research Institution for Additive Manufacturing Technologies
Ref	Reference
WP	Work package

Symbol	Unit	Definition
a	mm	Length of one side of the sample rock block
d	mm	Diameter of the laser beam on the rock surface
m_{BD}	g	Weight of the sample rock cube before laser drilling
$\overline{m_{\mathrm{BD}}}$	g	Average weight of the sample rock cube before laser drilling
m_{AD}	g	Weight of the sample rock cube after laser drilling
$\overline{m_{\mathrm{AD}}}$	g	Average weight of the sample rock cube after laser drilling
P_{L}	kW	Laser power
s_{BH}	mm	Depth of the borehole
$\overline{s_{\mathrm{BH}}}$	mm	Average depth of the borehole
T_{BD}	°C	Temperature of the rock before laser drilling
t	s	Power-on time
V_{BH}	cm³	Excavated volume of the borehole
$\overline{V_{\mathrm{BH}}}$	cm³	Average excavated volume of the borehole
λ	nm	Wavelength of the laser beam
ρ	g/cm³	Density of the rock

EXECUTIVE (or PUBLISHABLE) SUMMARY

The Fraunhofer IAPT analysed the direct laser and gas interaction with rocks in laboratory tests to determine the largest rock material excavation. Four different experimental sections were analysed for this purpose. The experimental sections are divided firstly into a normal condition at room temperature, secondly into a less cooled condition with approx. -15 °C, thirdly into a more cooled condition with approx. -55 °C, and fourthly into a wet condition in which the rock was saturated with water before laser drilling. The most important results are that the highest among of rock material excavation took place in the rock saturated with water by a factor of 1.67 for sandstone, 1.75 for granite, and 3.10 for limestone in comparison to the dry condition of the rocks. In addition, the depth of the laser drilled borehole increases by a factor of 1.21 for limestone, 1.24 for sandstone, and stays almost constant for granite. In sum, the cooled conditions have no effect on rock material excavation and show similar results to the normal condition.

1. INTRODUCTION

The development of the new cutting-edge technology for non-contact laser drilling requires a drill string with an innovative laser drill head and parameter-based modelling of the direct laser and gas interaction with the rocks, which the Fraunhofer IAPT is investigating in WP2 of the project. These findings are essential for creating a scaled model of a heat exchanger for deep geothermal energy exploitation, which is proposed in the DeepU project.

During drilling, the processing head immerses into the rock, whereby a free annular space must be created around the entire drill string, through which the molten rock can escape from the borehole and be pushed to the surface with the help of the gas. The processing head closes off the drill string at the bottom. Its main task is to direct a stream of nitrogen or inert gas onto the molten rock.

The innovative laser drill head was described in the report Deliverable D2.1. In the current report, the laser and gas interaction with rocks is presented to solve the question of maximum rock material excavation. Furthermore, this report extends the presented results in Deliverable D3.1 on the series of laser drilling experiments carried out together with the WP3 and WP8 team.

2. METHODOLOGY

The test series is divided into four experimental sections for each rock type (granite, sandstone, limestone). A detailed description of the individual experimental sections can be found in section 2.1. The analysis method is described in section 2.2.

2.1 EXPERIMENTAL SECTIONS

The boundary conditions listed in Tab. 1 present the four different experimental sections.

Table 1: Experimental sections and their conditions

Section	Condition
normal	rock approx. 20 °C
less cooled	rock approx. -15 °C
more cooled	rock approx. -55 °C
saturated	rock approx. 20 °C, rock saturated with water before laser drilling

The laser source is an Ytterbium fibre laser YLS-30000-S2 from IPG Photonics with a wavelength of λ = 1070 nm. Background information on the technology can be found in Eichler et al. [1], Hügel et al. [2], and Thieme [3]. For all experiments, the laser beam is directed onto the rock surface at a perpendicular angle. The distance to the rock surface is set so that a spot diameter of d = 10 mm is present on the rock surface. All blocks of rock are cubic and have a cut edge length a of roughly 50 mm. The laser power used is P_L = 12.5 kW with a power-on time t = 2 s. The schematic experimental setup is shown in Fig. 1.

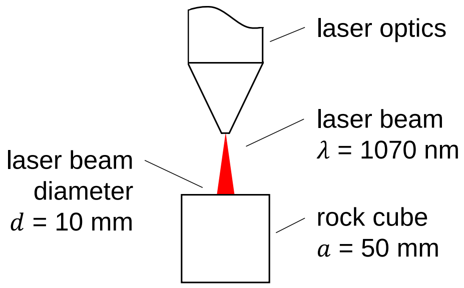

Figure 1: Schematic drawing of the experimental setup

2.2 ANALYTIC METHOD

A weight measurement is carried out before and after each experiment to determine the mass m_ES of the excavated rock material. A balance with an accuracy of 0.01 g is used for this. The temperature measurement is carried out with a pyrometer to document the sample temperature T before and after the laser process. The depth measurement is carried out using a calliper with an accuracy of 0.02 mm from the borehole bottom to the plane surface on the top of the rock. The excavated volume V_BH is calculated by combining the density ρ and the mass m_ES of the excavated rock material. The density ρ is taken from the results of the WP3 team. The equation is

$$V_\mathrm{BH} = \frac{m_\mathrm{ES}}{\rho}. \tag{1}$$

3. RESULTS

All samples were laser drilled with the setup described in section 2.1. The results are presented in the following sections.

3.1 GRANITE

Fig. 2 provides an overview of the experimental laser drilled result of selected granite samples for each experimental section.

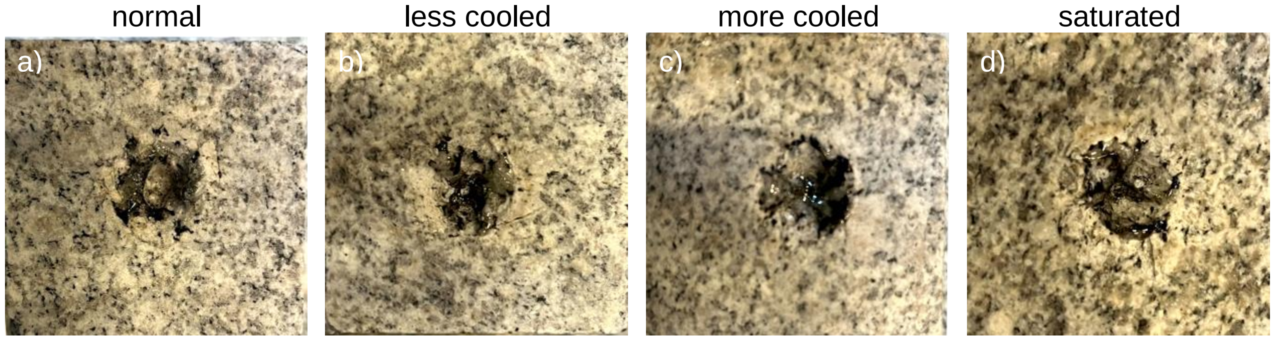

Figure 2: Overview of selected granite samples for each experimental section

With the weight measurement method using a balance with an accuracy of 0.01 g, the sample weight before and after laser drilling was carried out to calculate the average excavated volume $\overline{V_{\mathrm{BH}}}$ based on equation 1. For this purpose the measured density ρ = 2.63 g/cm³ [Ref. WP3] of the given granite slaps is used for all granite rock samples. The depth was measured using a calliper with an accuracy of 0.02 mm. Tab. 2 shows the average values for each experimental section.

Table 2: Average values of granite samples for each experimental section

Section	$\overline{m_{\mathrm{BD}}}$ in g	$\overline{m_{\mathrm{AD}}}$ in g	$\overline{V_{\mathrm{BH}}}$ in cm³	$\overline{s_{\mathrm{BH}}}$ in mm
normal	327.68	326.29	0.450	9.1
less cooled	316.58	315.44	0.433	4.5
more cooled	304.57	303.30	0.483	8.5
saturated	326.08	324.00	0.791	7.7

3.2 SANDSTONE

Fig. 3 provides an overview of the experimental laser drilled result of selected sandstone samples for each experimental section.

normal | less cooled | more cooled | saturated

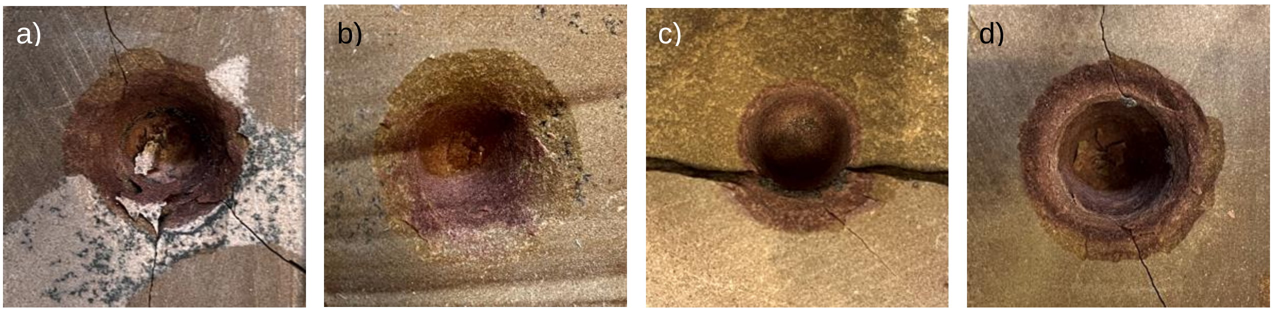

Figure 3: Overview of selected sandstone samples for each experimental section

With the weight measurement method using a balance with an accuracy of 0.01 g, the sample weight before and after laser drilling was carried out to calculate the average excavated volume $\overline{V_{\mathrm{BH}}}$ based on equation 1. For this purpose the measured density ρ = 2.60 g/cm³ [Ref. WP3] of the given sandstone slaps is used for all sandstone rock samples. The depth was measured using a calliper with an accuracy of 0.02 mm. Tab. 3 shows the average values for each experimental section.

Table 3: Average values of sandstone samples for each experimental section

Section	$\overline{m_{\mathrm{BD}}}$ in g	$\overline{m_{\mathrm{AD}}}$ in g	$\overline{V_{\mathrm{BH}}}$ in cm³	$\overline{s_{\mathrm{BH}}}$ in mm
normal	330.03	319.61	3.300	19.3
less cooled	325.92	314.27	4.481	19.0
more cooled	308.19	300.40	2.996	18.0
saturated	329.27	314.87	5.538	24.1

3.3 LIMESTONE

Fig. 4 provides an overview of the experimental laser drilled result of selected limestone samples for each experimental section.

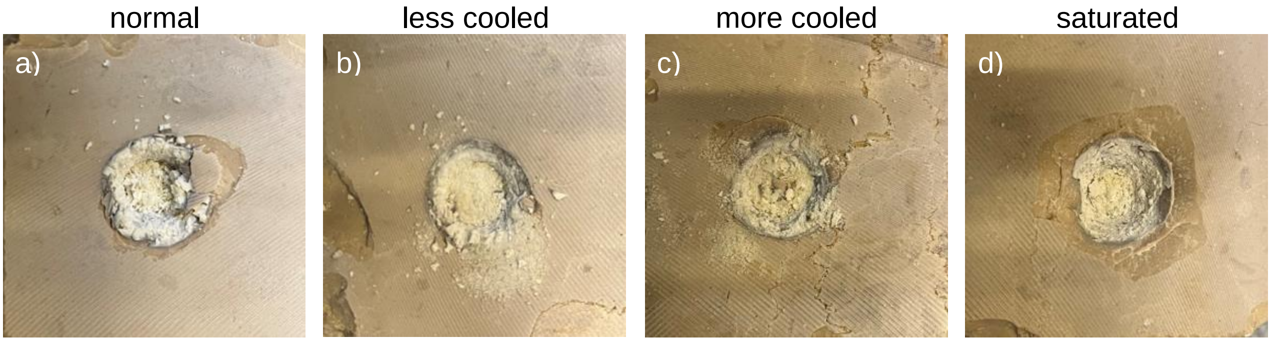

Figure 4: Overview of selected limestone samples for each experimental section

With the weight measurement method using a balance with an accuracy of 0.01 g, the sample weight before and after laser drilling was carried out to calculate the average excavated volume $\overline{V_{\mathrm{BH}}}$ based on equation 1. For this purpose the measured density ρ = 2.63 g/cm³ [Ref. WP3] of the given sandstone slaps is used for all sandstone rock samples. The depth was measured using a calliper with an accuracy of 0.02 mm. Tab. 4 shows the average values for each experimental section.

Table 4: Average values of limestone samples for each experimental section

Section	$\overline{m_{\mathrm{BD}}}$ in g	$\overline{m_{\mathrm{AD}}}$ in g	$\overline{V_{\mathrm{BH}}}$ in cm³	$\overline{s_{\mathrm{BH}}}$ in mm
normal	324.81	323.41	0.530	8.3
less cooled	331.44	330.26	0.449	8.5
more cooled	324.13	323.08	0.399	5.0
saturated	323.81	319.49	1.643	10.1

3.4 DATA SUMMARY

Fig. 5 summarizes the extracted results for all rock types from section 3.1 to 3.3 in one diagram with comparable bars.

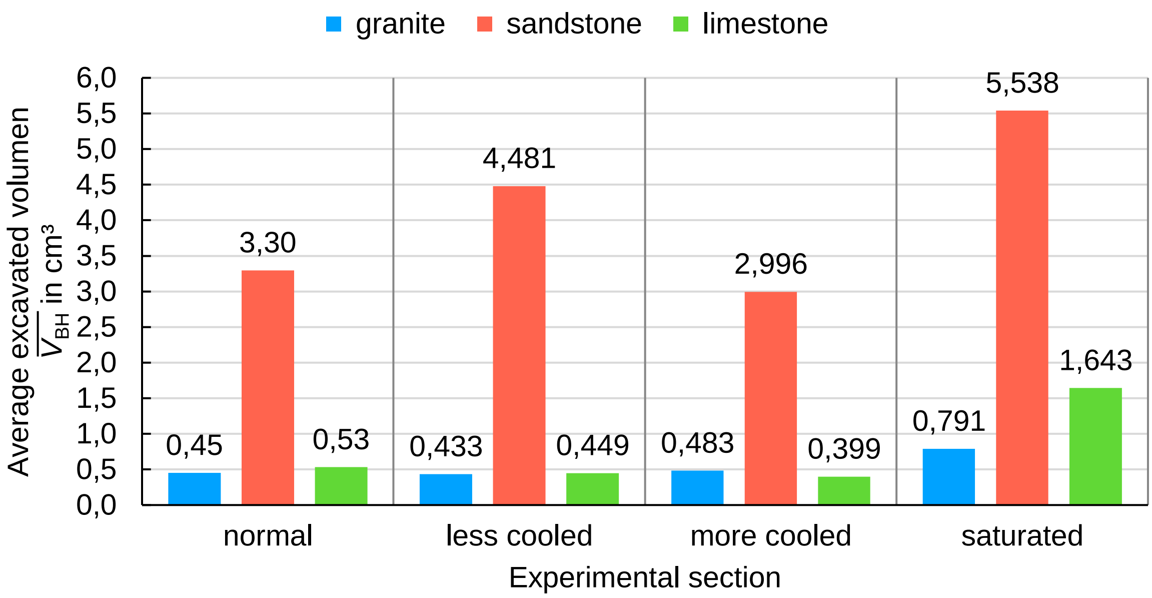

Figure 5: Diagram of average excavated volume of rock material for all rock types

For sandstone, the moisture in the rock results in a factor of 1.67 higher excavation than for dry sandstone. The same applies to granite, where the factor is even 1.75. Limestone comes out on top with more than three times (3.10) the excavation compared to dry limestone.

Furthermore, the moisture in the rock results in a borehole that is 1.24 times deeper for sandstone than for dry sandstone. This is also the case for limestone due to the same sponge effect as for sandstone. Here the factor is 1.21. The situation is different for granite. The borehole does not become deeper compared to dry granite.

4. CONCLUSION

Rocks saturated with water are the key for a high spallation rate, due to a high water vapour content resulting from the phase transition of the water from liquid to vapour during the interaction with the laser beam and thus, a high explosive force caused by the additional stresses created in the rock. The application of less or more cryogenic cooled rocks presents no further advantage and is good as the normal rock condition.

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