Experimental Investigation of Light on Rock

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Abstract

The phenomena of nonlinear acoustic wave modulation and slow dynamics are both associated with the fracture content. A rock has inherently a high fracture level, which is why we in this paper have used a new experimental set-up to measure the dynamic response of a rock beam exposed to light and heat. A short steel support was placed in the middle underneath a rock beam. The vertical position of the rock beam's end was measured with a laser triangulation displacement sensor. The beam was exposed to either blue light or heat, and the beam end deflection was monitored during the exposure and in the recovery after the exposure stopped. The largest effect is due to the temperature gradient from the thermal expansion. Qualitative differences exist, pointing to a non-thermal potential energy storage seen for blue light, while heat energy goes to kinetic energy (i.e. temperature).

Key Words: *Slow Dynamics, Rock Damage, Micro-Fractures, Material State Dynamics.*

Introduction

We have during many years used nonlinear acoustic methods to determine differences in the sub-micro-level structure for differently formed materials. One test showing the sensitivity is a 3-week fatigue test over 1.8 million cycles continuously monitoring the increase in micro-fractures (Hedberg 2013). All materials may be quantifiably estimated on the sub-micro-level structure, i.e. fractures on all geometrical scales, by mechanical parameters as distortion, attenuation, wave speed, and slow dynamics. Through the nonlinear acoustic methods, it is possible to make extremely sensitive measurements on a variety of materials of sub-micro-level damaged materials (Haller & Hedberg 2012). Rocks have a natural high level of fracture, which is one reason why many of these fundamental tests have been done on rocks. Materials' elastic modulus decrease when exposed to influences like mechanical impacts, ultrasound, magnetic fields, electricity and even humidity. Non-perfect atomic structures like rocks, concrete, or damaged metals exhibit a larger effect. The defects of the supramolecular structure of solids give rise to structural nonlinearity, which may exceed the conventional nonlinearities by two or three orders of magnitude Rudenko & Korobov 2010 and Hedberg & Rudenko 2011). This softening has most often been recorded by wave resonance measurements. An initial change is almost instantaneous, but the subsequent move towards equilibrium is slow (Lomnitz 1996) often taking hours or days, which is why the effect is called Slow Dynamics (TenCate & Shankland 1996 and Haller & Hedberg 2008) It has been interesting to see that an originally relatively undamaged material like steel, transforms its behavior towards being more like rocks, when the fracture content increases Haller & Hedberg (2008). The fracture-value is connected to other properties such as electrical conductivity, strength, sound velocity, and elastic modulus (Haller & Hedberg 2010). A change in one parameter carries with it changes in the other parameters; these changes are reversible, while being more pronounced for objects more fractures. In common descriptions, it is normally assumed that all the softening is caused by irreversible damage in the form of higher fracture contents, see e.g. (Branco R., Costa J., Antunes F 2012). There exist theories connecting this with highly delocalized wave functions used to explain an anomaly in thermal expansion of MgO (Wengeler H., Freund 1980). This may also predict emission of non-thermal photons and a change in radar reflectivity (Ouzounov D., Freund 2012). Again, we are not producing extra fractures, even though there would be effects in those processes too, see e.g. (Scholz 1996). The proposed emission of electromagnetic radiation makes it through reciprocity valid to expect different absorption for different incoming radiation. The infrared heat would be different than the visible blue light. One other support is that the slow dynamics exist due to interactions at the molecular level. This means that there will be electrons absorbing and emitting energy as they change their states.

Experimental Setup

A beam of rock with the dimensions of 650x30x16 mm is supported in its middle (Figure 1). An ILD 2200 Triangulating Laser is used as a sensor to measure the beam's deflection at one end. An RGB LED and an infrared heat source are used to condition the rock, i.e to reversibly change its material state. The reason for using the heat source, in addition to the light source, is that increase in the temperature of the rock is inevitable during light illumination. Thus, the question of whether the measured effects are due to light, heat, or both? To find an answer, one of these factors should be absent. Elimination of heat was not possible and it was decided to first use only heat, and then compare with both light and heat present. The whole setup is placed in an insulated chamber to minimize the environmental effect. The triangulating laser was covered with black paper in order to not be disturbed by the LED light. Two thermocouples are mounted on the top surface of the rock and two are attached to the beneath surface. Before start of measurements, the rock was placed in an insulated chamber for about ten days to be in a steady state condition.

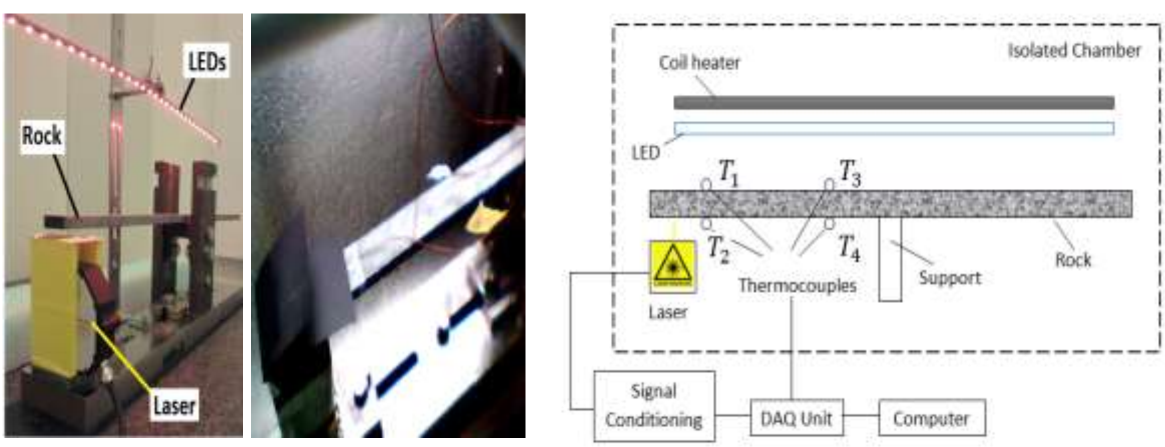


Figure 1 - LEFT: Test Setup for measurement of deflection of the rock; MIDDLE: Test setup is placed in the isolated chamber; RIGHT: Test setup is also shown schematically

The deflection near the free end of the beam is measured simultaneously as temperatures of the four points. The result when illuminating with Blue LED is shown in
Figure 3. The measurements for the case of conditioning with the heater are seen in
Figure 4.

Results and Discussions

When the source is above the rock, the deflection will be downward, and when the source is beneath, the deflection will be upward. This is mainly due to the temperature gradient causing a thermal expansion. The question is if the effect of the non-thermal softening and expansion can also be seen? In order to estimate the relative influences of the different effects, a theoretical model and an analysis must be done. Simulations based on this will be shown in what follows.

Effect of Cross Section Temperature Gradient

The recovery of deflection due to a temperature gradient can be modeled by an exponential function if the material is temperature independent. Using COMSOL simulation, it is shown that, irrespective of temperature distribution - if there is temperature gradient within the beam cross section - then the recovery of bending during the cooling can be modeled using the exponential function in Eq. 1. The curve fitting of the function to the simulation is shown in
Figure 2.

$$y(t) = a - ae^{\alpha t} \quad (1)$$

If the material characteristica are independent of time and temperature, then the time constant of recovery α in the above formula should be constant, and the amplitude should depend only on the intensity and distribution of the temperature.

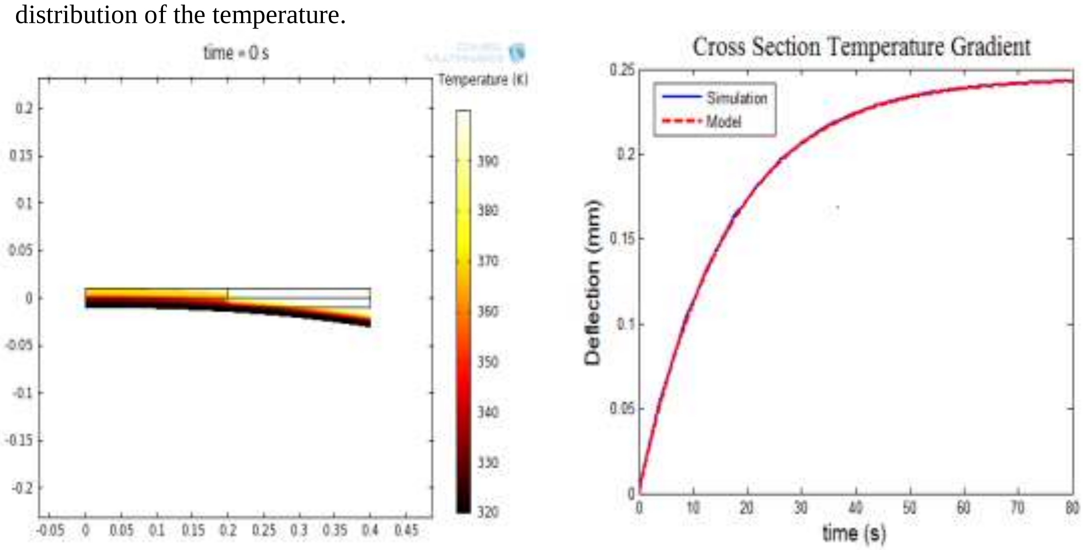


Figure 2 – Simulation of the effect of temperature gradient in the cross section using COMSOL; Simulation (blue line) and exponential model (dashed red line)

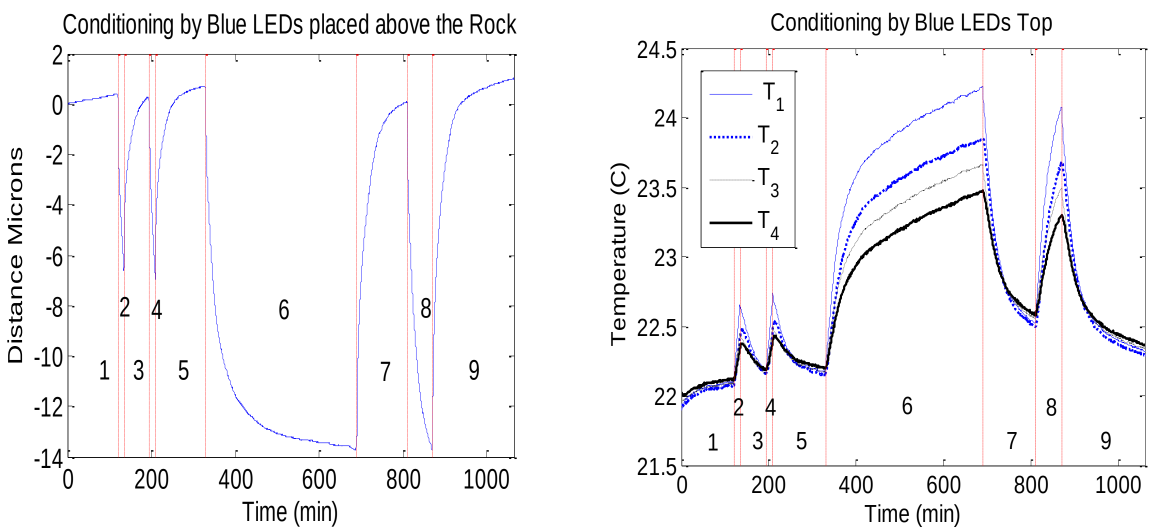


Figure 3 – Left: Distance of end of beam; Right: Four temperatures on the rock. During intervals 1 (=120 min), 3 (=60 min), 5 (=120 min), 7 (=120 min), 9 the LED was OFF. During intervals 2 (=15 min), 4 (=15 min), 6 (=360 min), and 8 (=60 min) the BLUE LED was ON.

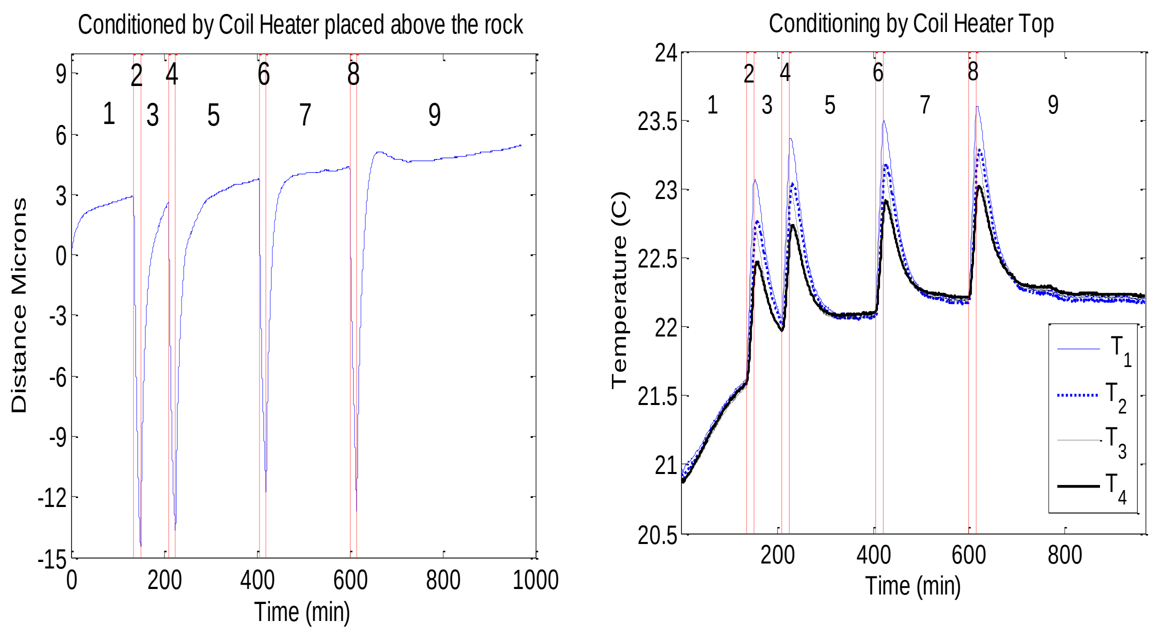


Figure 4 –Left: Distance of end of beam. ; Right: four temperatures on the rock. Heater OFF in the intervals 1 (=135 min), 3 (=60 min), 5 (=180 min), 7 (=180 min), and 9. In 2 (=15 min), 4 (=15 min), 6 (=15 min), and 8 (=15 min) the Heater was ON.

Deflection due to Young's Modulus variations

For a cantilever beam with a uniformly distributed load, the maximum deflection based on Euler-Bernoulli theory is given by:

$$\delta_{max} = u(L) = \frac{wL^4}{8EI} \tag{2}$$

Here L is the beam length and I is the area moment of inertia. The rock is 650x30x16 mm and since it is supported in the middle it is similar to cantilever beam with dimensions of 320x30x16 mm. Assuming the density of the Gabbro rock as ρ=2595 kg/m^3 and a module of elasticity E_0=80 GPa, the initial deflection will be:

$$\Rightarrow \delta_1 = u(L) = \frac{\frac{\rho bhLg}{L}L^4}{8E\frac{bh^3}{12}} = \frac{3\rho g L^4}{2E_1 h^2} = \frac{A}{E_1}$$

$$A = \frac{3\rho g L^4}{2h^2} = 453962.97\frac{\mathrm{N}}{\mathrm{m}} \Rightarrow \frac{\delta_2}{\delta_1} = \frac{E_1}{E_2} \Rightarrow \frac{\delta_2 - \delta_1}{\delta_1} = \frac{\Delta\delta}{\delta_1} = \frac{E_1 - E_2}{E_2} = \frac{-\Delta E}{E_1 + \Delta E}$$

$$\Rightarrow \Delta E/E_1 = \frac{\frac{-\Delta\delta}{\delta_1}}{1 + \frac{\Delta\delta}{\delta_1}} = \frac{\frac{-\Delta\delta}{A}}{\frac{1}{E_1} + \frac{\Delta\delta}{A}} \tag{3}$$

Based on Equation (3), the required percentage of reduction in Young's modulus E per micron of end deflection for an initial value of E at 80 GPa is around 5%. We do therefore not expect to detect a deflection due to the change in the Young's Modulus.

Deflection Due to Expansion of Rock

The deflection due to expansion of the rock can be estimated as follows:

$$L_1 = L_0 + \alpha\Delta T,\ \ h_1 = h_0 + \alpha\Delta T,\ \ b_1 = b_0 + \alpha\Delta T$$

$$\rho_1 = \frac{\rho_0 b_0 h_0 L_0}{b_1 h_1 L_1} \Rightarrow \Delta\delta = \delta_1 - \delta_0 = \frac{3g}{2E}\left(\frac{\rho_1 L_1^4}{h_1^2} - \frac{\rho_0 L_0^4}{h_0^2}\right)$$

Based on the beam data, the magnitude of this effect is on the order of -3. The deflection due to material expansion or elongation of rock is negligible.

Errors Due To Elongation of Support

The length of the support of the rock change due to variation in temperature. It is made of steel and its change in length per degree Kelvin is:

$$\Delta L = L_0 \alpha \Delta T = 0.1 \times 13 \times 10^{-6} \times 1 = 1.3\ Microns$$

Therefore, for a one degree temperature increase of the support, there is about 1.3 Microns deflection. This is not negligible.

Analysis of the Recovery Curves

In summary, we expect to see mainly the effects from the expansion gradient primarily due to temperature, and from the elongation of the support. To reduce the latter one, the support was covered with paper and aluminum foil.

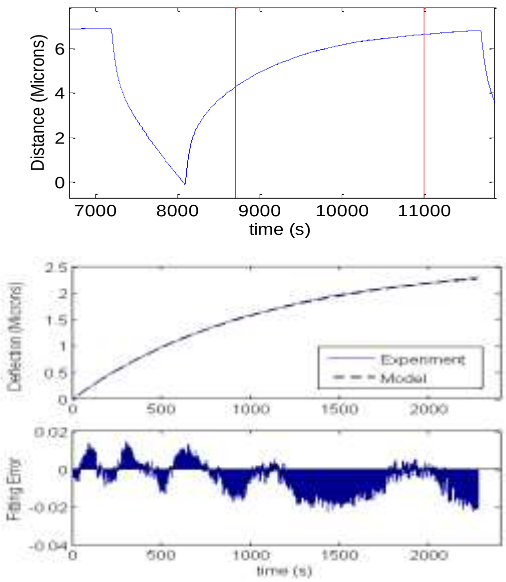


Figure 5 – Blue LED Recovery - one exponential function fits the selected part between red lines in the top figure The time constant is obtained as: α =0.000958

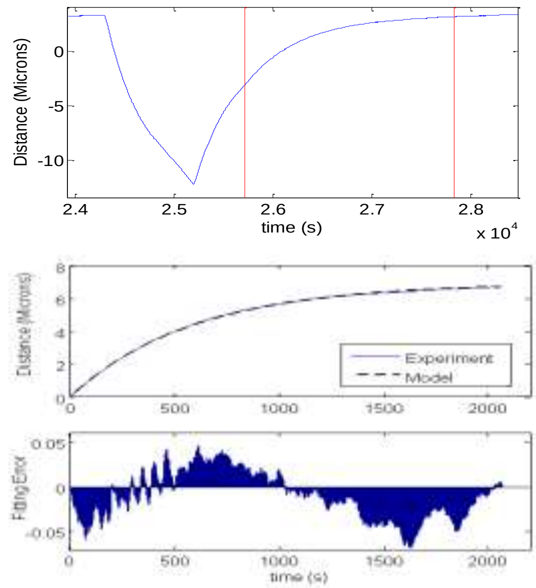
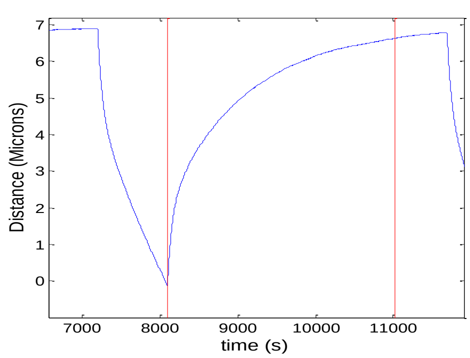


Figure 6 – Heater Recovery - one exponei function fits the selected part between red lines in left figure The time constant is obtained α =0.00169

For both cases of conditioning, with Blue LED and coil heater, it is seen that a single exponential function can be fitted to the recovery curve when its beginning part is neglected. This is shown in Figure 5 for Blue LED, and in Figure 6 for the coil heater. For the recoveries with the Blue LED, it was not possible to fit the whole part with a single exponential. Using two exponentials, one of them having the time constant obtained from the previous analysis, a very good fit was achieved. When conditioning with heat, it is possible for the third recovery (region 7 in
Figure 4) to fit the whole data with a good accuracy with one exponential with the same time constant previously. However, this was not the case for the other two.



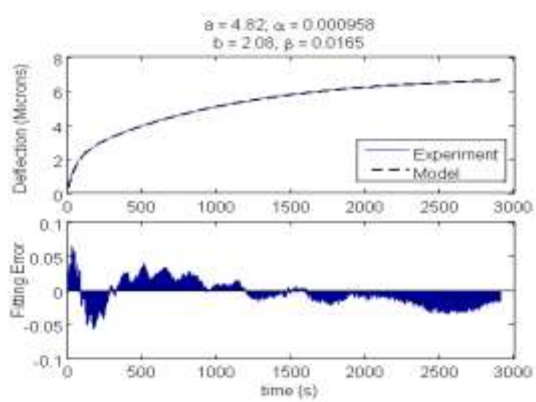


Figure 7 – Two exponential function fits the selected part between red lines in the left figure; The time constant of one of them is already selected as: $\alpha =$0.000958, a=4.82 and then fixing this value, “a”, “b” and $= 0.0165$, b=2.08 are found.

The time constants of recovery for light and heat are different.

Conclusion and Future Work

When conditioning from the above, the recovery of temperature gradient and elongation have opposite directions. Neglecting the initial parts of the recovery curves, it is possible to fit one exponential to the data for both heat and blue light. With blue light it was possible to do that for all recoveries but it is not possible to fit the whole recovery with only exponential model. On the other hand, for the case when the source was coil heater, neglecting the initial part of the recovery curves, only for one of the recovery curves was possible to fit exponential model to it with a good accuracy. Interestingly, it was possible to have a good fit for whole part of the same recovery using only one exponential with the time constant same as what was obtained neglecting initial part. With Blue LED there are other effects than heat, and the time constants are different. This is an indicator of non-thermal light effects pointing to the existence of potential energies being activated, and not only the kinetic energies (temperature).

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